

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

Zepp Health Corporation,
Petitioner,

v.

WORCESTER POLYTECHNIC INSTITUTE;
THE RESEARCH FOUNDATION
FOR THE STATE UNIVERSITY OF NEW YORK
Patent Owners.

IPR2025-00522
U.S. Patent No. 9,713,428

DECLARATION OF SYLVIA D. HALL-ELLIS, PH.D.

INTRODUCTION

1. My name is Sylvia D. Hall-Ellis. I have been retained as an expert by Procopio, Cory, Hargreaves & Savitch, LLP.

2. I have written this declaration at the request of Procopio, Cory, Hargreaves & Savitch to provide my expert opinion regarding the authenticity and public availability of a printed publication. My declaration sets forth my opinions in detail and provides the basis for my opinions regarding the public availability of this publication.

3. I reserve the right to supplement or amend my opinions, and bases for them, in response any additional evidence, testimony, discovery, argument, and/or other additional information that may be provided to me after the date of this declaration.

4. I am being compensated for my time spent working on this matter at my normal consulting rate, plus reimbursement for any additional reasonable expenses. My compensation is not in any way tied to the content of this declaration, the substance of my opinions, or the outcome of this litigation. I have no other interests in this proceeding or with any of the parties.

5. All of the materials that I considered are discussed explicitly in this declaration.

I. QUALIFICATIONS

6. I am currently an Adjunct Professor in the School of Information at San José State University. I obtained a Master of Library Science from the University of North Texas in 1972 and a Ph.D. in Library and Information Science from the University of Pittsburgh in 1985. Over the last fifty years, I have held various positions in the field of library and information resources. I was first employed as a librarian in 1966 and have been involved in the field of library sciences since, holding numerous positions.

7. I am a member of the American Library Association (ALA) and its Association for Library Collections & Technical Services (ALCTS) Division, and I served on the Committee on Cataloging: Resource and Description (which wrote the new cataloging rules) and as the chair of the Committee for Education and Training of Catalogers and the Competencies and Education for a Career in Cataloging Interest Group. I also served as the Chair of the ALCTS Division's Task Force on Competencies and Education for a Career in Cataloging. Additionally, I have served as the Chair for the ALA Office of Diversity's Committee on Diversity, as a member of the national Board of Directors for REFORMA, as a member of the Editorial Board for the ALCTS premier cataloging journal, *Library Resources and Technical Services*, as a Co-Chair for the Library Research Round Table (LRRT) of ALA, and a member of the LRRT

Nominating Committee. Currently I serve as a member of the CORE Margaret Mann Citation Committee.

8. I have also given over one hundred presentations in the field, including several related to library cataloging systems and Machine-Readable Cataloging (“MARC”) standards. My current research interests include library cataloging systems, metadata, and organization of electronic resources.

9. My full curriculum vitae is attached hereto as Attachment A to this declaration.

II. PRELIMINARIES

A. Scope of Declaration and Legal Standards

10. I am not an attorney and will not offer opinions on the law. I am, however, rendering my expert opinion on the authenticity of the document referenced herein and when and how the document was disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the document before January 21, 2011.

11. I am informed by counsel that a printed publication qualifies as publicly accessible as of the date it was disseminated or otherwise made available such that a person interested in and ordinarily skilled in the relevant subject matter could locate it through the exercise of ordinary diligence.

12. While I understand that the determination of public accessibility under the foregoing standard rests on a case-by-case analysis of the facts particular to an individual publication, I also understand that a printed publication is rendered “publicly accessible” if it is cataloged and indexed by a library such that a person interested in the relevant subject matter could locate it exercising reasonable diligence (*i.e.*, I understand that cataloging and indexing by a library in a manner that permits a person of ordinary skill in the relevant subject matter to locate the publication is sufficient, though there are other ways that a printed publication may qualify as publicly accessible). One manner of sufficient indexing is indexing according to subject matter category. I understand that the cataloging and indexing by a single library of a single instance of a particular printed publication is sufficient, even if the single library is in a foreign country. I understand that, even if access to a library is restricted, a printed publication that has been cataloged and indexed therein is publicly accessible so long as a presumption is raised that the portion of the public concerned with the relevant subject matter would know of the printed publication. I also understand that the cataloging and indexing of information that would guide a person interested in the relevant subject matter to the printed publication, such as the cataloging and indexing of an abstract for the printed publication, is sufficient to render the printed publication publicly accessible.

13. I understand that routine business practices, such as general library cataloging and indexing practices, can be used to establish an approximate date on which a printed publication became publicly accessible.

B. Persons of Ordinary Skill in the Art

14. I am told by counsel that the subject matter of this proceeding relates generally to physiological monitoring technologies and signal processing as used in physiological monitoring technologies.

15. I have been informed by counsel that a “person of ordinary skill in the art at the time of the invention” (POSITA) is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the inventions. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific principles applicable to the pertinent field.

16. I am told by counsel that a person of ordinary skill in the art (“POSITA”) at the time of the purported invention of the ’428 Patent would have had a working knowledge of physiological monitoring technologies and/or signal processing as used in physiological monitoring technologies. The POSITA would have had a bachelor’s degree in an academic discipline related to electrical, computer, software, optical, or biomedical technologies, in combination with two years of work experience related to the capture and processing of data or information signals, or designing and using biomedical sensors or systems,

including but not limited to physiological monitoring technologies. Alternatively, a POSITA would have had a master's degree in one of the above academic disciplines with one year of work experience as described above. Additional education can substitute work experience, and vice versa.

17. It is my opinion that such a person would have been engaged in research, learning through study and practice in the field and possibly through formal instruction the bibliographic resources relevant to his or her research. Before January 21, 2011, such a person would have had access to a vast array of long-established print resources concerning data services handlers or database management systems (and methods of using the systems), as well as to a rich set of online resources providing indexing information, abstracts, and full text services for development of both data services handlers and database management systems.

18. Based on my experience working in research libraries with researchers having the qualifications described above, or even lesser qualifications, it is my opinion that such researchers would have been able to locate the material discussed herein on their own or with the assistance of a research librarian with relative ease using the tools and resources described herein.

III. LIBRARY CATALOGING PRACTICES

19. In preparing this declaration, I used authoritative databases, such as the OCLC bibliographic database, the Library of Congress Online Catalog, and the

Library of Congress Subject Authorities, to confirm citation details of the various publications discussed. Unless I note otherwise below in reference to a specific serial publication, it is my expert opinion that this standard protocol was followed for the serial publication discussed below.

20. Based on my experience working in research libraries with researchers having the qualifications described above, or even lesser qualifications, it is my opinion that such researchers would have been able to locate the material discussed herein on their own or with the assistance of a research librarian with relative ease using the tools and resources described herein.

A. INDEXING

21. A researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. However, date information for indexing entries is often unavailable. This is especially true for online indices.

22. Indexing services use a wide variety of controlled vocabularies to

provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

23. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document.

24. Before the widespread development of online databases to index articles in journals, magazines, conference papers, and technical declarations, libraries purchased printed volumes of indices. Graduate library school education mandated that students learn about the bibliographic control of disciplines, the prominent indexing volumes, and searching strategies required to use them effectively and efficiently. Half of the courses that I studied in library school were focused on bibliography and resources in academic disciplines.

25. Librarians consulted information seekers to verify citations, check availability in union catalogs, printed books catalogs, the OCLC database, and make formal requests for materials (*e.g.*, books, conference proceedings, journal articles). Requests were transmitted using Telex machines, rudimentary email systems, and the United States Postal Service. During my career, I have performed

and supervised staff who handled these resource sharing tasks.

26. A citation of a document by another is evidence that the document was publicly available and in use no later than the publication date of the citing document.

27. A researcher may discover material relevant to his or her topic in a variety of ways. A citation of a document by another is evidence that the document was publicly available and in use no later than the publication date of the citing document. One common means of discovery is to search for relevant information in an index of periodicals and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from a publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. However, date information for indexing entries is often unavailable. This is especially true for online indices.

28. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The Library of Congress Subject Authorities includes standard forms of terms and cross references that are included in bibliographic records. Subject headings are terms that an individual seeking a document regardless of format can enter in the search bar of the online catalog. Subjects also connect an authenticated term (one

included in the Library of Congress subject headings list) with related, broader, and narrower terms. The formats in which these access terms are presented vary from service to service.

29. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document. Prominent indexing services include *Scopus*, the *IEEE Xplore* database, the *ACM Digital Library*, *Google Scholar*, and the *Internet Archive*.

B. MARC RECORDS AND THE ONLINE LIBRARY CATALOG

30. I am fully familiar with the library cataloging standard known as the MARC standard, which is an industry-wide standard method of storing and organizing library catalog information.¹ MARC was first developed in the 1960s by the Library of Congress. A MARC-compatible library is one that has a catalog consisting of individual MARC records for each of its items. Today, MARC is the primary communications protocol for the transfer and storage of bibliographic

¹ The full text of the standard is available from the Library of Congress at <http://www.loc.gov/marc/bibliographic/> (last accessed January 9, 2025).

metadata in libraries.

31. Since at least the early 1970s and continuing to the present day, MARC has been the primary communications protocol for the transfer and storage of bibliographic metadata in libraries.² As explained by the Library of Congress:

You could devise your own method of organizing the bibliographic information, but you would be isolating your library, limiting its options, and creating much more work for yourself. Using the MARC standard prevents duplication of work and allows libraries to better share bibliographic resources. Choosing to use MARC enables libraries to acquire cataloging data that is predictable and reliable. If a library were to develop a “home-grown” system that did not use MARC records, it would not be taking advantage of an industry-wide standard whose primary purpose is to foster communication of information.

Using the MARC standard also enables libraries to make use of commercially available library automation systems to manage library operations. Many systems are available for libraries of all sizes and are designed to work with the MARC format. Systems are maintained and improved by the vendor so that libraries can benefit from the latest advances in computer technology. The MARC standard also allows libraries to replace one system with another with the assurance that their data will still be compatible.³

32. Thus, almost every major library in the world is MARC-compatible.

See Library of Congress, *Frequently Asked Questions (FAQ)* (“MARC is the

² A complete history of the development of MARC can be found in *MARC: Its History and Implications* by Henrietta D. Avram (Washington, DC: Library of Congress, 1975) and available online from the Hathi Trust at <https://babel.hathitrust.org/cgi/pt?id=mdp.39015034388556;view=1up;seq=1> (last accessed January 9, 2025).

³ Library of Congress, “Why Is a MARC Record Necessary?,” <http://www.loc.gov/marc/umb/um01to06.html#part2> (last accessed January 9, 2025).

acronym for Machine-Readable Cataloging. It defines a data format that emerged from a Library of Congress-led initiative that began fifty years ago. It provides the mechanism by which computers exchange, use, and interpret bibliographic information, and its data elements make up the foundation of most library catalogs used today.”).⁴ MARC is the ANSI/NISO Z39.2-1994 standard (reaffirmed in 2016) for Information Interchange Format. The full text of the standard is available from the Library of Congress.⁵

33. A MARC record comprises several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follow. For example, a work’s title is recorded in Field 245; the primary author of the work is transcribed in Field 100; an item’s International Standard Book Number (“ISBN”) consisting of ten or thirteen digits is transcribed in Field 020; an item’s International Standard Serial Number (“ISSN”) is transcribed in Field 022; the Library of Congress classification notation is recorded in Field 050; and the publication date is recorded in Field 260 under the subfield “c.” If a work is a periodical, then its publication frequency is recorded in Field 310, and the publication dates (*e.g.*, the first and last

⁴ Library of Congress, “MARC Frequently Asked Questions (FAQ),” <https://www.loc.gov/marc/faq.html> (last accessed January 9, 2025).

⁵ Library of Congress, “Bibliographic Data,” <http://www.loc.gov/marc/bibliographic/> (last accessed January 9, 2025).

publication) are recorded in Field 362, which is also referred to as the enumeration/chronology field.⁶

34. The library that created the record is recorded in Field 040 in subfield “a” with a unique library code. When viewing the MARC record online via the OCLC bibliographic database, (initially known as the Ohio College Library Center) hovering over this code with the mouse reveals the full name of the library. I have used this method of “mousing over” the library codes in the OCLC database to identify the originating library for the MARC records discussed in this declaration. Where this “mouse over” option was not available, I consulted the Directory of OCLC Libraries to identify the institution that created the MARC record.⁷

35. MARC records also include several fields that include subject matter classification information. An overview of MARC record fields is available through the Library of Congress.⁸ For example, 6XX fields are termed “Subject

⁶ Library of Congress, “3XX – Physical Description, Etc. Fields – General Information,” <http://www.loc.gov/marc/bibliographic/bd3xx.html> (last accessed January 9, 2025).

⁷ OCLC, “Directory of OCLC members,” <https://www.oclc.org/en/contacts/libraries.html> (last accessed January 9, 2025).

⁸ Library of Congress, *supra* note 13.

Access Fields.”⁹ Among these, for example, is the 650 field; this is the “Subject Added Entry – Topical Term” field.¹⁰ The 650 field is a “[s]ubject added entry in which the entry element is a topical term.” These entries “are assigned to a bibliographic record to provide access according to generally accepted thesaurus-building rules (e.g., *Library of Congress Subject Headings* (LCSH), *Medical Subject Headings* (MeSH)).” *Id.* Further, MARC records include call numbers, which themselves include a classification number. For example, the 050 field is the “Library of Congress Call Number.”¹¹ A defined portion of the Library of Congress Call (LCC) Number is the classification number, and “source of the classification number is *Library of Congress Classification* and the *LC Classification-Additions and Changes*.” Thus, included in the 050 field is a subject matter classification. Further, the 082 field is the “Dewey Decimal Call Number.”¹² A defined portion of the Dewey Decimal Call (DDC) Number is the classification

⁹ Library of Congress, “6XX – Subject Access Fields-General Information,” <http://www.loc.gov/marc/bibliographic/bd6xx.html> (last accessed January 9, 2025).

¹⁰ Library of Congress, “650 – Subject Added Entry-Topical Term (R),” <http://www.loc.gov/marc/bibliographic/bd650.html> (last accessed January 9, 2025).

¹¹ Library of Congress, “050 – Library of Congress Call Number (R),” <http://www.loc.gov/marc/bibliographic/bd050.html> (last accessed January 9, 2025).

¹² Library of Congress, “082 – Dewey Decimal Classification Number (R),” <http://www.loc.gov/marc/bibliographic/bd082.html> (last accessed January 9, 2025).

number, and “source of the classification number is the *Dewey Decimal Classification and Relative Index*.” Thus, included in the 082 field is a subject matter classification. Each item in a library has a single classification number. A library selects a classification scheme (e.g., the Library of Congress classification scheme just described or a similar scheme such as the Dewey Decimal classification scheme) and uses it consistently. When the Library of Congress assigns the LCC classification number, it appears as part of the 050 field. When the Library of Congress assigns the DDC classification number, it appears as part of the 082 field. If a local library assigns the classification number, it appears in a 090 field. In either scenario, the MARC record includes a classification number that represents a subject matter classification.

C. OCLC

36. The OCLC was created “to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific,

literary and educational knowledge and information.”¹³ Among other services, OCLC and its members are responsible for maintaining the WorldCat database,¹⁴ used by independent and institutional libraries throughout the world.

37. OCLC also provides its members online access to MARC records through its OCLC bibliographic database. When an OCLC member institution acquires a work, it creates a MARC record for this work in its computer catalog system in the ordinary course of its business. MARC records created at the Library of Congress are directly uploaded or may be tape-loaded into the OCLC database through a subscription to MARC Distribution Services daily or weekly. Once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from a participating institution, the MARC record is then made available to any other OCLC members online, and therefore made available to the public. Accordingly, once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from the Library of Congress or another library anywhere in the world, any publication corresponding to the MARC record has been cataloged and indexed according to its subject matter such that a person interested in that subject matter could, with reasonable diligence, locate and access

¹³ Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Inc., available at <https://www.oclc.org/content/dam/oclc/membership/articles-of-incorporation.pdf> (last accessed January 9, 2025).

¹⁴ WorldCat, <http://www.worldcat.org/> (last accessed January 9, 2025).

the publication through any library with access to the OCLC bibliographic database or through the Library of Congress.

38. When an OCLC member institution creates a new MARC record, OCLC automatically supplies the date of creation for that record. The date of creation for the MARC record appears in the fixed field (008), characters 00 through 05. The MARC record creation date reflects the date on which, or shortly after which, the item was first acquired or cataloged. Initially, field 005 of the MARC record is automatically populated with the date the MARC record was created in year, month, day format (YYYYMMDD) (some of the newer library catalog systems also include hour, minute, second (HHMMSS)). Thereafter, the library's computer system may automatically update the date in field 005 every time the library updates the MARC record (*e.g.*, to reflect that an item has been moved to a different shelving location within the library). Field 005 is visible when viewing a MARC record via an appropriate computerized interface. The date upon which the most recent update to field 005. Thus, when an item's MARC record has been printed to hardcopy—as is the case with the exhibits to this declaration—the date reflected in field 008 is necessarily on or after the date the library first cataloged and indexed the underlying item.

39. Once one library has cataloged and indexed a publication by creating a MARC record for that publication, other libraries that receive the publication do

not create additional MARC records—the other libraries instead rely on the original MARC record. They may update or revise the MARC record to ensure accuracy, but they do not replace or duplicate it. This practice does more than save libraries from duplicating labor. It also enhances the accuracy of MARC records. Further, it allows librarians around the world to know that a particular MARC record is authoritative (in contrast, a hypothetical system wherein duplicative records were created would result in confusion as to which record is authoritative).

40. The date of creation of the MARC record by a cataloger at an OCLC member institution reflects when the underlying item is accessible to the public. Upwards of two-thirds to three-quarters of book sales to libraries come from a jobber or wholesaler for online and print resources. These resellers make it their business to provide books to their customers as fast as possible, often providing turnaround times of only a single day after publication. Libraries purchase a significant portion of the balance of their books directly from publishers themselves, which provide delivery on a similarly expedited schedule. In general, libraries make these purchases throughout the year as the books are published and shelve the books as soon thereafter as possible in order to make the books available to their patrons. Thus, books are generally available at libraries across the country within just a few days of publication.

IV. PUBLICATIONS

A. Ex-1005 (“Asada”)

41. Attached hereto as Ex-1005 is a copy of the journal article titled “Mobile Monitoring with Wearable Photoplethysmographic Biosensors” by H. Harry Asada, Phillip Shaltis, Andrew Reisner, Sokwoo Rhee, and Reginald C. Hutchinson (hereafter “Asada”). The Asada article was published in Volume 22, Number 3 of the journal *IEEE Engineering in Medicine and Biology Magazine* and was found in the Otto G. Richter Library at the University of Miami (Coral Gables, Florida). The Asada article appears beginning on page 28 of this issue dated May/June 2003. Ex-1005 is a true and correct copy of the Asada article (pages 28-40) that I understand is being submitted as an exhibit in this proceeding. Specifically, the text of the article is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1005 was found within the custody of a library – a place where an authentic copy of this journal would likely be. Ex-1005 is a true and correct copy in a condition that creates no suspicion about its authenticity.

42. The Asada article is also available from the publisher’s *IEEE Xplore* database,¹⁵ through the National Library of Medicine,¹⁶ and the digital repositories

¹⁵ <https://ieeexplore.ieee.org/document/1213624>

*ResearchGate*¹⁷ and *Semantic Scholar*.¹⁸ The *IEEE Xplore* database indicates that the Asada article was added on June 30, 2003.

43. Attached hereto as Attachment 1A is a true and correct copy of the MARC record for the journal *IEEE Engineering in Medicine and Biology Magazine* from the Otto G. Richter Library at the University of Miami online catalog. The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 1A occurred on May 18, 2016, as shown in field 005 (“20160518”). I personally identified and retrieved the MARC record that is Attachment 1A.

44. Based on finding a copy of Ex-1005 in the Otto G. Richter Library at the University of Miami and MARC record in its online library catalog attached as Attachment 1A, it is my opinion that the Asada article published in the journal *IEEE Engineering in Medicine and Biology Magazine* was publicly available in a digital version on June 30, 2003, as shown on the *IEEE Xplore* website, and in print on July 1, 2003, as shown by the stamp on the cover of Ex-1005. In common practice these stamps are applied at or around the time the volume is entered into

¹⁶ <https://pubmed.ncbi.nlm.nih.gov/12845817/>

¹⁷

https://www.researchgate.net/publication/10674436_Mobile_Monitoring_with_Wearable_Photopecthysmographic_Biosensors

¹⁸ <https://www.semanticscholar.org/paper/Mobile-monitoring-with-wearable-biosensors.-Asada-Shaltis/38bcf0bd4f8c35ff54d292d37cbdca1da677f3f5>

the library's collection and the volume is made available to library patrons within a short time thereafter. Attachment 1A also shows that Ex-1005 was catalogued with a descriptor term reading "Biomedical engineering \$v Periodicals" (see Attachment 1B, Library of Congress subject heading sh2007102015) in the 650 field.

45. As noted in the holdings information (362 field), the Otto G. Richter Library at the University of Miami has received the journal *IEEE Engineering in Medicine and Biology Magazine* since June 1982 and continues to receive the publication. In view of the MARC record for Ex-1005, the Asada article was publicly available in a digital version on June 30, 2003, as shown on the *IEEE Xplore* website, and in print on July 1, 2003, because the serial title had been received, cataloged, and indexed in the Otto G. Richter Library at the University of Miami and made part of its online catalog.

46. Attached hereto as Attachment 1C is a true and correct copy of the MARC record for the journal *IEEE Engineering in Medicine and Biology Magazine* obtained from the OCLC bibliographic database. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 1C, that library code is "CLU," which means that the MARC record for this serial was cataloged in the University of California – Los Angeles Libraries. As can be seen in field 008 ("Date entered on file") in the

MARC record for this exhibit, a cataloger in the University of California – Los Angeles Libraries created OCLC record number 8878354 on October 20, 1982, as shown in field 008 (“821020”). The library continued to update and enhance the MARC record to meet current cataloging rules until the publication ceased operations in June 2010 (see second field 362). The most recent enhancement to Attachment 1C occurred on August 10, 2022, as shown in field 005 (“20220810”). I personally identified and retrieved the MARC record that is Attachment 1C. The “BLvl” entry in Attachment 1C is “s,” which indicates that the journal *IEEE Engineering in Medicine and Biology Magazine* is a serial publication. Field 310 of Attachment 1C reads “Bimonthly, \$b 1995-2010.” Accordingly, the MARC record for Ex-1005 corresponds to the journal *IEEE Engineering in Medicine and Biology Magazine* from the time the serial title adopted the current title and includes the date of the Asada article.

47. Attachment 1C includes an entry in field 050 (“R856.A1 \$b E54”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system), an entry in field 060 (“W1 \$b IE222H”)—as described above, a subject matter classification number consistent with the National Library of Medicine classification system (analogous to the Dewey Decimal classification system), and an entry in field 082 (“610/.28”)—as described above, a subject

matter classification number consistent with the Dewey Decimal classification system. Attachment 1C further includes a descriptor terms reading “Biomedical engineering \$v Periodicals” (see Attachment 1B, Library of Congress subject heading sh2007102015) in the 650 field. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 1C was indexed according to its subject matter by virtue of at least four independently sufficient classifications: the field 050 entry, the field 060 entry, the field 082 entry, and the field 650 entry. As of October 20, 1982, the MARC record attached hereto as Attachment 1C was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that subscribed to the serial, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

48. WorldCat indicates that the journal *IEEE Engineering in Medicine and Biology Magazine* as cataloged in the University of California – Los Angeles Libraries is currently available from 736 libraries.¹⁹ In view of the above, this issue of the journal *IEEE Engineering in Medicine and Biology Magazine* was publicly available in a digital version on June 30, 2003, and in print on July 1, 2003, because the serial title had been cataloged and indexed in the University of

¹⁹ <https://search.worldcat.org/title/8878354>

California – Los Angeles Libraries, made part of the OCLC bibliographic database, and received, cataloged, and indexed in the Otto G. Richter Library at the University of Miami. For these reasons, it is my opinion that Ex-1005 was published and accessible to the public in a digital version on June 30, 2003, and in print on July 1, 2003.

B. Ex-1009 (“Chon-2009”)

49. Attached hereto as Ex-1009 is a copy of the journal article titled “Estimation of Respiratory Rate from Photoplethysmogram Data Using Time–Frequency Spectral Estimation” by Ki H. Chon, Shishir Dash, and Kihwan Ju (hereafter “Chon-2009”). The Chon-2009 article was published in Volume 56, Number 8 of the journal *IEEE Transactions on Biomedical Engineering* and was found in the Health Sciences Library at the University of Florida (Gainesville, Florida). The Chon-2009 article appears beginning on page 2054 of this issue dated August 2009. Ex-1009 is a true and correct copy of the Chon-2009 article (pages 2054-2063) that I understand is being submitted as an exhibit in this proceeding. Specifically, the text of the article is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1009 was found within the custody of a library – a place where an authentic copy of this journal would likely be. Ex-1009 is a true and correct copy in a condition that creates no

suspicion about its authenticity.

50. The Chon-2009 article is also available from the publisher's *IEEE Xplore* database,²⁰ through the National Library of Medicine,²¹ and the digital repository *ResearchGate*.²² The *IEEE Xplore* database indicates that the Chon-2009 article was added on April 14, 2009.

51. Attached hereto as Attachment 2A is a true and correct copy of the MARC record for the journal *IEEE Transactions on Biomedical Engineering* from the Health Sciences Library at the University of Florida online catalog. The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 2A occurred on January 31, 2023, as shown in field 005 ("20230131"). I personally identified and retrieved the MARC record that is Attachment 2A.

52. Based on finding a copy of Ex-1009 in the Health Sciences Library at the University of Florida and MARC record in its online library catalog attached as Attachment 2A, it is my opinion that the Chon-2009 article published in the journal *IEEE Transactions on Biomedical Engineering* was publicly available in a digital

²⁰ <https://ieeexplore.ieee.org/document/4814699>

²¹ <https://pubmed.ncbi.nlm.nih.gov/19369147/>

²²

https://www.researchgate.net/publication/224401747_Estimation_of_Respiratory_Rate_From_Photoplethysmogram_Data_Using_Time-Frequency_Spectral_Estimation

version on April 14, 2009, as shown on the *IEEE Xplore* website, and in print on July 28, 2009, as shown by the stamp on the cover of Ex-1009. In common practice these stamps are applied at or around the time the volume is entered into the library's collection and the volume is made available to library patrons within a short time thereafter. Attachment 2A also shows that Ex-1009 was catalogued with three descriptor terms reading "Biomedical engineering \$v Periodicals" (see Attachment 1B, Library of Congress subject heading sh2007102015), "Medical electronics \$v Periodicals" (see Attachment 2B, Library of Congress subject heading sh2010101221), and "Medical physics \$v Periodicals" (see Attachment 2C, Library of Congress subject heading sh85083001 and Attachment 2D, Library of Congress subject heading sh85099890) in the 650 fields.

53. As noted in the holdings information (362 field), the Health Sciences Library at the University of Florida has received the journal *IEEE Transactions on Biomedical Engineering* since January 1964 and continues to receive the publication. In view of the MARC record for Ex-1009, the Chon-2009 article was publicly available in a digital version on April 14, 2009, as shown on the *IEEE Xplore* website, and in print on July 28, 2009, because the serial title had been received, cataloged, and indexed in the Health Sciences Library at the University of Florida and made part of its online catalog.

54. Attached hereto as Attachment 2E is a true and correct copy of the

MARC record for the journal *IEEE Transactions on Biomedical Engineering* obtained from the OCLC bibliographic database. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 2E, that library code is “DLC,” which means that the MARC record for this serial was cataloged in the Library of Congress. As can be seen in field 008 (“Date entered on file”) in the MARC record for this exhibit, a cataloger in the Library of Congress created OCLC record number 1752544 on November 1, 1975, as shown in field 008 (“751101”). The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 2E occurred on April 21, 2021, as shown in field 005 (“20210421”). I personally identified and retrieved the MARC record that is Attachment 2E. The “BLvl” entry in Attachment 2E is “s,” which indicates that the journal *IEEE Transactions on Biomedical Engineering* is a serial publication. Field 310 of Attachment 2E reads “Monthly, \$b Jan. 1979-.” Accordingly, the MARC record for Ex-1009 corresponds to the journal *IEEE Transactions on Biomedical Engineering* from the time the serial title adopted the current title and includes the date of the Chon-2009 article.

55. Attachment 2E includes an entry in field 050 (“R895.A1 \$b I25”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification

system), an entry in field 060 (“W1 [\$b] I223”)—as described above, a subject matter classification number consistent with the National Library of Medicine classification system (analogous to the Dewey Decimal classification system), and an entry in field 082 (“610.28”)—as described above, a subject matter classification number consistent with the Dewey Decimal classification system. Attachment 2E further includes three descriptor terms reading “Biomedical engineering \$v Periodicals” (see Attachment 1B, Library of Congress subject heading sh2007102015), “Medical electronics \$v Periodicals” (see Attachment 2B, Library of Congress subject heading sh2010101221), and “Medical physics \$v Periodicals” (see Attachment 2C, Library of Congress subject heading sh85083001 and Attachment 2D, Library of Congress subject heading sh85099890) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 2E was indexed according to its subject matter by virtue of at least four independently sufficient classifications: the field 050 entry, the field 060 entry, the field 082 entry, and the field 650 entries. As of November 1, 1975, the MARC record attached hereto as Attachment 2E was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that subscribed to the serial, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an

individual library.

56. WorldCat indicates that the journal *IEEE Transactions on Biomedical Engineering* as cataloged in the Library of Congress is currently available from 794 libraries.²³ In view of the above, this issue of the journal *IEEE Transactions on Biomedical Engineering* was publicly available in a digital version on April 14, 2009, and in print on July 28, 2009, because the serial title had been cataloged and indexed in the Library of Congress, made part of the OCLC bibliographic database, and received, cataloged, and indexed in the Health Sciences Library at the University of Florida. For these reasons, it is my opinion that Ex-1009 was published and accessible to the public in a digital version on April 14, 2009, and in print on July 28, 2009.

C. Ex-1007 (“Delorme”)

57. Attached hereto as Ex-1007 is a copy of a conference paper published in the volume titled *Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference* found on CD-ROM in the TIB – Leibniz Information Centre for Technology and Natural Sciences and University Library (Hanover, Germany). The conference paper titled “Automatic Artifact Rejection for EEG Data Using High-Order Statistics and Independent Component Analysis” by Arnaud Delorme, Scott Makeig, and Terrence Sejnowski

²³ <https://search.worldcat.org/title/1752544>

(hereafter “Delorme”) appears beginning on page 9. The 3rd International Independent Component Analysis and Blind Source Decomposition Conference was held on December 9-13, 2003, in San Diego, California. Ex-1007 is a true and correct copy of the Delorme conference paper (pages 9-12). I downloaded the Delorme conference paper from the digital repository *CiteSeer*^x that is Ex-1007.²⁴ Specifically, the text of the Delorme conference paper is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1007 was found within the custody of a library – a place where, if authentic, a copy of this conference proceedings volume would likely be. Ex-1007 is a true and correct copy in a condition that creates no suspicion about authenticity.

58. The Delorme conference paper is also available from the digital repository at the Swartz Center for Computational Neuroscience (La Jolla, California)²⁵ and the digital repositories *ResearchGate*²⁶ and *Semantic Scholar*.²⁷

²⁴

<https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=c4967e2a7f082f3a35fd8f2e5faf5ad8fbe340b2>

²⁵ <https://sccn.ucsd.edu/~arno/mypapers/delormefinal01.pdf>

²⁶

https://www.researchgate.net/publication/2552520_Automatic_Artifact_Rejection_For_EEG_Data_Using_High-Order_Statistics_And_Independent_Component_Analysis

59. Attached hereto as Attachment 3A is a true and correct copy of the metadata record for this conference proceedings CD-ROM from the TIB – Leibniz Information Centre for Technology and Natural Sciences and University Library (Hanover, Germany) online catalog. The library ownership is indicated by the presence of the library’s name (TIBKAT) at the bottom of the record. I personally identified and retrieved the library catalog record which is Attachment 3A.

60. Based on finding a copy of the CD-ROM (Ex-1007) in the TIB – Leibniz Information Centre for Technology and Natural Sciences and University Library and metadata record in its online library catalog attached as Attachment 3A, it is my opinion that the volume titled *Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference* was publicly available at the TIK after December 13, 2001.

61. Attached hereto as Attachment 3B is a true and correct copy of the MARC record for the CD-ROM titled *Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference* obtained from the OCLC bibliographic database. I personally identified and retrieved the MARC record that is Attachment 3B. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For

²⁷ <https://www.semanticscholar.org/paper/AUTOMATIC-ARTIFACT-REJECTION-FOR-EEG-DATA-USING-AND-Delorme-Makeig/c4967e2a7f082f3a35fd8f2e5faf5ad8f8e340b2>

Attachment 3B, that library code is “YQU,” which means that the MARC record for this conference proceedings volume was cataloged in the St. Lucia Campus Library of the University of Queensland (Brisbane, Queensland, Australia). As can be seen in field 008 (“Date entered on file”) of the MARC record for this exhibit, a cataloger in the St. Lucia Campus Library of the University of Queensland created OCLC record number 62540072 on April 4, 2003 (“030404”). The library continues to update the MARC record to meet current cataloging rules. The most recent enhancement to the MARC record occurred on April 8, 2024, as shown in field 005 (“20240408”).

62. Attachment 3B also shows that Ex-1007 was catalogued with three authenticated descriptor terms reading “Signal processing \$x Digital techniques \$v Congresses” (see Attachment 3C, Library of Congress subject heading sh2008111654), “Multivariant analysis \$v Congresses” (Attachment 3D, Library of Congress subject heading sh2008107554), and “Neural networks (Computer science) \$v Congresses” (Attachment 3E, Library of Congress subject heading sh2008108385) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 3B was indexed according to its subject matter by virtue of at least three independently sufficient classifications: the field 111 entry (conference name), the field 245 entry (title of volume), and the field 650 entries. Further, as of April 4, 2003, the MARC record

attached hereto as Attachment 3B was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that acquired the conference proceedings volume, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

63. WorldCat indicates that the conference volume on CD-ROM titled *Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference* as cataloged in the St. Lucia Campus Library of the University of Queensland is currently available from 2 libraries.²⁸ In view of the above, the CD-ROM version of the volume titled *Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference* was publicly available on or shortly after April 4, 2003, because by that date it had been received, cataloged, and indexed in the St. Lucia Campus Library of the University of Queensland and made part of the OCLC bibliographic database. For these reasons, it is my opinion that Ex-1007 was published and publicly accessible on or shortly after April 4, 2003.

D. Ex-1010 (“Greco”)

64. Attached hereto as Ex-1010 is a copy of the journal article titled “Kurtosis, Renyi’s Entropy and Independent Component Scalp Maps for the

²⁸ <https://search.worldcat.org/title/62540072>

Automatic Artifact Rejection from EEG data” by Antonino Greco, Nadia Mammone, Francesco Carlo Morabito, and Mario Versaci (hereafter “Greco”). The Greco article was published in Volume 2, Number 4 of the *International Journal of Signal Processing* and was found in the University of Wisconsin – Madison Libraries. The Greco article appears beginning on page 240 of this issue dated Fall 2006. Ex-1010 is a true and correct copy of the Greco article (pages 240-244) that I understand is being submitted as an exhibit in this proceeding. Specifically, the text of the article is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1010 was found within the custody of a library – a place where an authentic copy of this journal would likely be. Ex-1010 is a true and correct copy in a condition that creates no suspicion about its authenticity.

65. The Greco article is also available through the digital repositories *ResearchGate*²⁹ and *Semantic Scholar*.³⁰ The *ResearchGate* indicates a January 2006 publication date.

²⁹

https://www.researchgate.net/publication/228934042_Kurtosis_Renyi's_entropy_and_independent_component_scalp_maps_for_the_automatic_artifact_rejection_from_EEG_data

³⁰ <https://www.semanticscholar.org/paper/Kurtosis%2C-Renyi's-Entropy-and-Independent-Component-Greco-Mammone/127edf5da396031a0306a3de18f49c4767ae1432>

66. Attached hereto as Attachment 4A is a true and correct copy of the MARC record for the *International Journal of Signal Processing* from the University of Wisconsin – Madison Libraries online catalog. The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 4A occurred on February 26, 2024, as shown in field 005 (“20240226”). I personally identified and retrieved the MARC record that is Attachment 4A.

67. As noted in the holdings information (362 field), the University of Wisconsin – Madison Libraries has received the *International Journal of Signal Processing* since Winter 2005 and continues to receive the publication.

68. Based on finding a digital copy of Ex-1010 in the University of Wisconsin – Madison Libraries and MARC record in its online library catalog attached as Attachment 4A, it is my opinion that the Greco article published in the *International Journal of Signal Processing* was publicly available in a digital version by January 31, 2006, as shown on the *ResearchGate* website because the serial title had been received, cataloged, and indexed in the University of Wisconsin – Madison Libraries and made part of its online catalog.

69. Attachment 4A includes an entry in field 050 (“TK5102.9”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification

system). Attachment 4A also shows that Ex-1010 was catalogued with a descriptor term reading “Signal processing \$v Periodicals” (see Attachment 4B, Library of Congress subject heading sh2010113087) in the 650 field.

70. Attached hereto as Attachment 4C is a true and correct copy of the MARC record for the *International Journal of Signal Processing* obtained from the OCLC bibliographic database. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 4C, that library code is “HUA,” which means that the MARC record for this serial was cataloged in the University of Hong Kong Library (Hong Kong, Special Administrative Region, China). As can be seen in field 008 (“Date entered on file”) in the MARC record for this exhibit, a cataloger in the University of Hong Kong Library created OCLC record number 321350076 on April 12, 2006, as shown in field 008 (“060412”). The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 4C occurred on April 29, 2024, as shown in field 005 (“2024049”). I personally identified and retrieved the MARC record that is Attachment 4C. The “BLvl” entry in Attachment 4C is “s,” which indicates that the *International Journal of Signal Processing* is a serial publication. Field 310 of Attachment 4C reads “Quarterly.” Accordingly, the MARC record for Ex-1010 corresponds to the *International Journal of Signal Processing* from the time the serial title began

publication and includes the date of the Greco article.

71. Attachment 4C includes an entry in field 050 (“TK5102.9”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system). Attachment 4C further includes a descriptor term reading “Signal processing \$v Periodicals” (see Attachment 4B, Library of Congress subject heading sh2010113087) in the 650 field. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 4C was indexed according to its subject matter by virtue of at least two independently sufficient classifications: the field 050 entry and the field 650 entry. As of April 12, 2006, the MARC record attached hereto as Attachment 4C was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that subscribed to the serial, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

72. WorldCat indicates that the *International Journal of Signal Processing* as cataloged in the University of Hong Kong Library is currently available from 98 libraries.³¹ In view of the above, this issue of the *International Journal of Signal Processing* was publicly available in a digital version by January

³¹ <https://search.worldcat.org/title/321350076>

31, 2006, because the serial title had been cataloged and indexed in the University of Hong Kong Library, made part of the OCLC bibliographic database, and received, cataloged, and indexed in the University of Hong Kong Library. For these reasons, it is my opinion that Ex-1010 was published and accessible to the public in a digital version by January 31, 2006.

E. Ex-1013 (“Zhao”)

73. Attached hereto as Ex-1013 is a copy of the journal article titled “Estimation of Time-Varying Coherence Function Using Time-Varying Transfer Functions” by He Zhao, Sheng Lu, Rui Zou, Kihwan Ju, and Ki H. Chon (hereafter “Zhao”). The Zhao article was published in Volume 33, Number 11 of the *Annals of Biomedical Engineering* and was found in the Linda Hall Library of Science, Engineering & Technology (Kansas City, Missouri). The Zhao article appears beginning on page 1582 of this issue dated November 2005. Ex-1013 is a true and correct copy of the Zhao article (pages 1582-1594) that I understand is being submitted as an exhibit in this proceeding. Specifically, the text of the article is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1013 was found within the custody of a library – a place where an authentic copy of this journal would likely be. Ex-1013 is a true and correct copy in a condition that creates no suspicion about its authenticity.

74. The Zhao article is also available from the publisher, Springer,³² through the National Library of Medicine,³³ and through the digital repositories *ResearchGate*³⁴ and *Semantic Scholar*.³⁵ The publisher's website indicates a November 2005 publication date.

75. Attached hereto as Attachment 5A is a true and correct copy of the MARC record for the *Annals of Biomedical Engineering* from the Linda Hall Library of Science, Engineering & Technology online catalog. The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 5A occurred on November 23, 2020, as shown in field 005 ("20201123"). I personally identified and retrieved the MARC record that is Attachment 5A.

76. As noted in the holdings information (362 field), the Linda Hall Library of Science, Engineering & Technology has received the *Annals of Biomedical Engineering* since September 1972 and continues to receive the publication. The issue from which the Zhao article was copied was transferred from the Engineering Societies Library in January 1995 to the Linda Hall Library

³² <https://link.springer.com/article/10.1007/s10439-005-7045-4>

³³ <https://pubmed.ncbi.nlm.nih.gov/17271669/>

³⁴ https://www.researchgate.net/publication/7427917_Estimation_of_Time-Varying_Coherence_Function_Using_Time-Varying_Transfer_Functions

³⁵ <https://www.semanticscholar.org/paper/Estimation-of-time-varying-coherence-function-using-Zhao-Lu/8bf3b01003b842d20c79df7e2171822237eb0ef0>

of Science, Engineering & Technology (see Attachment 5A, field 599).

77. Based on finding a copy of Ex-1013 in the Linda Hall Library of Science, Engineering & Technology and MARC record in its online library catalog attached as Attachment 5A, it is my opinion that the Zhao article published in the *Annals of Biomedical Engineering* was publicly available in a digital version by November 30, 2005, as shown on the publisher's website because the serial title had been received, cataloged, and indexed in the Linda Hall Library of Science, Engineering & Technology and made part of its online catalog.

78. Attachment 5A includes an entry in field 050 ("R856.A1 \$b A55")—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system) and an entry in field 060 ("W1 \$b AN564")—as described above, a subject matter classification number consistent with the National Library of Medicine classification system (analogous to the Dewey Decimal classification system). Attachment 5A also shows that Ex-1013 was catalogued with a descriptor term reading "Biomedical engineering \$v Periodicals" (see Attachment 1B, Library of Congress subject heading sh2007102015) in the 650 field.

79. Attached hereto as Attachment 5B is a true and correct copy of the MARC record for the *Annals of Biomedical Engineering* obtained from the OCLC bibliographic database. As previously noted, the library that created the record is

recorded in field 040 with a unique library code. For Attachment 5B, that library code is “LGG,” which means that the MARC record for this serial was cataloged in the McGill University Libraries (Montreal, Quebec, Canada). As can be seen in field 008 (“Date entered on file”) in the MARC record for this exhibit, a cataloger in the McGill University Libraries created OCLC record number 427179353 on December 19, 1980, as shown in field 008 (“801219”). The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 5B occurred on May 8, 2022, as shown in field 005 (“20220508”). I personally identified and retrieved the MARC record that is Attachment 5B. The “BLvl” entry in Attachment 5B is “s,” which indicates that the *Annals of Biomedical Engineering* is a serial publication. Accordingly, the MARC record for Ex-1013 corresponds to the *Annals of Biomedical Engineering* from the time the serial title began publication and includes the date of the Zhao article.

80. Attachment 5B includes an entry in field 050 (“R856.A1 \$b A55”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system), an entry in field 060 (“W1 \$b AN564”)—as described above, a subject matter classification number consistent with the National Library of Medicine classification system (analogous to the Dewey Decimal classification

system), and an entry in field 082 (“620 ANNALS”)—as described above, a subject matter classification number consistent with the Dewey Decimal classification system. Attachment 5B further includes two descriptor terms reading “Biomedical engineering \$v Periodicals” (see Attachment 1B, Library of Congress subject heading sh2007102015) and “Biomedical engineering” (see Attachment 5C, Library of Congress subject heading sh85014237) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 5B was indexed according to its subject matter by virtue of at least four independently sufficient classifications: the field 050 entry, the field 060 entry, the field 082 entry, and the field 650 entries. As of December 19, 1980, the MARC record attached hereto as Attachment 5B was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that subscribed to the serial, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

81. WorldCat indicates that the *Annals of Biomedical Engineering* as cataloged in the McGill University Library is currently available from 1,201 libraries.³⁶ In view of the above, this issue of the *Annals of Biomedical Engineering* was publicly available by November 30, 2005, because the serial title

³⁶ <https://search.worldcat.org/title/427179353>

had been cataloged and indexed in the McGill University Library, made part of the OCLC bibliographic database, and received, cataloged, and indexed in the Linda Hall Library of Science, Engineering & Technology. For these reasons, it is my opinion that Ex-1013 was published and accessible to the public in a digital version by November 30, 2005.

F. Ex-1008 (“Chon-2008”)

82. Attached hereto as Ex-1008 is a copy of the journal article titled “Analysis of Nonstationarity in Renal Autoregulation Mechanisms Using Time-Varying Transfer and Coherence Functions” by Ki H. Chon, Yuru Zhong, Leon C. Moore, Niels H. Holstein-Rathlou, and William A. Cupples (hereafter “Chon-2008”). The Chon-2008 article was published in Volume 56, Number 8 of the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* and was found in the National Library of Medicine (Bethesda, Maryland). The Chon-2008 article appears beginning on page R821 of this issue dated September 2008. Ex-1008 is a true and correct copy of the Chon-2008 article (pages R821-R828) that I understand is being submitted as an exhibit in this proceeding. Specifically, the text of the article is complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Ex-1008 was found within the custody of a library – a place where an authentic copy of this journal would

likely be. Ex-1008 is a true and correct copy in a condition that creates no suspicion about its authenticity.

83. The Chon-2008 article is also available from the publisher's website,³⁷ through the National Library of Medicine,³⁸ and the digital repository *Semantic Scholar*.³⁹ The publisher's website indicates that the Chon-2008 article was added on May 21, 2008.

84. Attached hereto as Attachment 6A is a true and correct copy of the MARC record for the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* from the National Library of Medicine online catalog. The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 6A occurred on January 28, 2025, as shown in field 005 ("20250128"). I personally identified and retrieved the MARC record that is Attachment 6A.

85. Based on finding a copy of Ex-1008 in the National Library of Medicine and MARC record in its online library catalog attached as Attachment 6A, it is my opinion that the Chon-2008 article published in the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* was publicly

³⁷ <https://journals.physiology.org/doi/epdf/10.1152/ajpregu.00582.2007>

³⁸ <https://pubmed.ncbi.nlm.nih.gov/18495831/>

³⁹ <https://www.semanticscholar.org/paper/Analysis-of-nonstationarity-in-renal-autoregulation-Chon-Zhong/eb873e5254f30056831bfd232738ac5cb4231eb6>

available in a digital version on May 21, 2008, as shown on the publisher's website. Attachment 6A also shows that Ex-1008 was catalogued with three descriptor terms reading "Physiological Phenomena \$x physiology \$v periodical" (see Attachment 6B, National Library of Medicine subject heading D010829), "Homeostasis \$x physiology \$v periodical" (see Attachment 6C, National Library of Medicine subject heading D006706), and "Physiology, Comparative \$v periodical" (see Attachment 6D, National Library of Medicine subject heading D010828) in the 650 fields.

86. As noted in the holdings information (362 field), the National Library of Medicine has received the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* since January 1977 and continues to receive the publication. In view of the MARC record for Ex-1008, the Chon-2008 article was publicly available in a digital version on May 21, 2008, as shown on the publisher's website because the serial title had been received, cataloged, and indexed in the National Library of Medicine and made part of its online catalog.

87. Attached hereto as Attachment 6E is a true and correct copy of the MARC record for the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* obtained from the OCLC bibliographic database. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 6E, that library code is "DLC," which means

that the MARC record for this serial was cataloged in the Library of Congress. As can be seen in field 008 (“Date entered on file”) in the MARC record for this exhibit, a cataloger in the Library of Congress created OCLC record number 3022253 on June 7, 1977, as shown in field 008 (“770607”). The library continues to update and enhance the MARC record to meet current cataloging rules. The most recent enhancement to Attachment 6E occurred on February 3, 2023, as shown in field 005 (“20230203”). I personally identified and retrieved the MARC record that is Attachment 6E. The “BLvl” entry in Attachment 6E is “s,” which indicates that the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* is a serial publication. Field 310 of Attachment 6E reads “Monthly, \$b <Feb. 1983->.” Accordingly, the MARC record for Ex-1008 corresponds to the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* from the time the serial title adopted the current title and includes the date of the Chon-2008 article.

88. Attachment 6E includes an entry in field 050 (“QP33 \$b .A43”)—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system), an entry in field 060 (“W1 [\$b] AM507P”)—as described above, a subject matter classification number consistent with the National Library of Medicine classification system (analogous to the Dewey Decimal classification system), and

an entry in field 082 (“596/.01/05”)—as described above, a subject matter classification number consistent with the Dewey Decimal classification system. Attachment 6E further includes two descriptor terms reading “Physiology, Comparative \$v Periodicals” (see Attachment 6F, Library of Congress subject heading sh2010106364) and “Biological control systems \$v Periodicals” (see Attachment 6G, Library of Congress subject heading sh85014173 and Attachment 2D, Library of Congress subject heading sh85099890) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 6E was indexed according to its subject matter by virtue of at least four independently sufficient classifications: the field 050 entry, the field 060 entry, the field 082 entry, and the field 650 entries. As of June 7, 1977, the MARC record attached hereto as Attachment 6E was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that subscribed to the serial, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

89. WorldCat indicates that the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* as cataloged in the Library of

Congress is currently available from 678 libraries.⁴⁰ In view of the above, this issue of the *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* was publicly available in a digital version on May 21, 2008, because the serial title had been cataloged and indexed in the Library of Congress, made part of the OCLC bibliographic database, and received, cataloged, and indexed in the National Library of Medicine. For these reasons, it is my opinion that Ex-1008 was published and accessible to the public in a digital version on May 21, 2008.

V. SUMMARY OF OPINIONS

90. In view of the foregoing, it is my opinion that the publication described above was publicly available no later than the corresponding date listed in the table below:

Exhibit	Publication	Publicly Available By
(Ex-1005)	Asada, H. Harry, Phillip Shaltis, Andrew Reisner, Sokwoo Rhee, and Reginald C. Hutchinson. "Mobile Monitoring with Wearable Photoplethysmographic Biosensors." <i>IEEE Engineering in Medicine and Biology Magazine</i> , vol. 22, no. 3 (May/June 2003): 28-40.	July 1, 2003

⁴⁰ <https://search.worldcat.org/title/3022253>

Exhibit	Publication	Publicly Available By
(Ex-1009)	Chon, Ki H., Shishir Dash, and Kihwan Ju. “Estimation of Respiratory Rate from Photoplethysmogram Data Using Time–Frequency Spectral Estimation.” <i>IEEE Transactions on Biomedical Engineering</i> , vol. 56, no. 8 (August 2009): 2054-2063.	July 28, 2009
(Ex-1007)	Delorme, Arnaud, Scott Makeig, and Terrence Sejnowski. “Automatic Artifact Rejection for EEG Data Using High-Order Statistics and Independent Component Analysis.” <i>Proceedings of the 3rd International Independent Component Analysis and Blind Source Decomposition Conference</i> (pp. 9-12). San Diego, CA: Institute for Neural Computation, University of California, 2001.	April 4, 2003
(Ex-1010)	Greco, Antonino, Nadia Mammone, Francesco Carlo Morabito, and Mario Versaci. “Kurtosis, Renyi’s Entropy and Independent Component Scalp Maps for the Automatic Artifact Rejection from EEG data. <i>International Journal of Signal Processing</i> , vol. 2, no. 4 (Fall 2006): 240-244.	January 31, 2006
(Ex-1013)	Zhao, He, Sheng Lu, Rui Zou, Kihwan Ju, and Ki H. Chon. “Estimation of Time-Varying Coherence Function Using Time-Varying Transfer Functions.” <i>Annals of Biomedical Engineering</i> , vol. 33, no. 11 (November 2005): 1582–1594.	November 30, 2005
(Ex-1008)	Chon, Ki H., Yuru Zhong, Leon C. Moore, Niels H. Holstein-Rathlou, and William A. Cupples. “Analysis of Nonstationarity in Renal Autoregulation Mechanisms Using Time-Varying Transfer and Coherence Functions.” <i>American Journal of Physiology. Regulatory, Integrative and Comparative Physiology</i> , vol. 295, issue 3 (September 2008): R821–R828.	May 21, 2008

91. In signing this Declaration, I recognize that the Declaration will be filed as evidence in a case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I also recognize that I may be subject to cross-examination in the case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

92. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

DATED: February 3, 2025

By: *Sylvia D. Hall-Ellis*
Sylvia D. Hall-Ellis, Ph.D.

ATTACHMENT A

CURRICULUM VITAE SYLVIA D. HALL-ELLIS

EDUCATION

Ph.D., University of Pittsburgh, Pittsburgh, Pennsylvania, 1985
 M.P.S., University of Denver, Denver, Colorado, 2014
 Post Graduate Studies, University of Texas – San Antonio, Texas, 1975-1976
 M.L.S., University of North Texas, Denton, Texas, 1972
 B.A., Rockford University, Rockford, Illinois, 1971

PROFESSIONAL EXPERIENCE

- 1981- Consultant for higher education, non-profit organizations, and corporations.**
- 2002- Adjunct Professor, School of Information, San José State University, San José, California.** Serve as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), “core courses,” and special topics.
- 2014-2016 Director, Grants and Resource Development, Colorado Community College System.**
 Provided leadership and vision to foster the continued growth of rigorous scholarship, innovative projects, and creative work for statewide system, 13 campuses, and 50 teaching sites serving 155,000 students. Responsible for leadership and ensured efficient functioning of contract and grants in compliance with state & federal requirements and successful implementation and management. Served as a subject matter expert and liaison for college Grant Directors for all issues relating to grants and subcontracts.
- 2010-2014 Senior Grant Administrator, Morgridge College of Education, University of Denver (Colorado).** Provided leadership and vision to foster continued growth of rigorous scholarship, innovative research, and creative work in the Morgridge College of Education. Ensure that contract and grants processes function effectively and efficiently for 60 faculty and researchers with a focus on the successful progression and efficient management of grants totaling \$13M. Worked effectively and collegially with Department Chairs and Program Coordinators on operational grant-related management activities and with a broad range of internal and external constituencies. Supported the dissemination and promotion of faculty research and scholarship to outside constituents at conferences and through publications. Assisted Principal Investigators and grant project teams by coaching, mentoring, and financial management.
- 2011-2013 Interim Director & Assistant Dean, Westminster Law Library, Sturm College of Law, University of Denver.** Planned, organized, and directed all administrative activities for the library serving students, faculty, and alumni; oversaw the employment, retention, promotion, transfer and termination of library personnel; represented the library at professional conferences and public meetings; created and promoted a climate and culture of acceptance for new programs and services, a positive high-quality image of the law library, and that reflect the organization’s values, encourage excellent performance, and reward high productivity and innovation; provided leadership and set strategic direction of the organization; ensured that the library provided excellent customer service through solution-oriented staff response to patron needs and by responsiveness and continuous improvement of the organization; promoted, developed, and maintained positive working relationships with colleagues and customers including key stakeholders and groups, higher education institutions, the legal community, other regional libraries and districts statewide, and national library organizations.

- 2007-2014** **Associate Professor, Library & Information Science, Morgridge College of Education, University of Denver (Colorado).** Served in leadership role and worked collaboratively in program, college, campus and community environments. Advised and supervised students, taught core and specialized courses at the graduate level in an integrative, student-centered learning environment. Served on LIS, College, and University committees, and maintained working relationships with colleagues in other academic units and information professionals in the Rocky Mountain region and beyond. Served on and chair doctoral student dissertation committees. Oversaw and facilitated the College and LIS graduate student association.
- 2002-2007** **Assistant Professor, Library & Information Science, College of Education, University of Denver (Colorado).** Served as tenure-track faculty member teaching graduate students in “core courses,” resource description and access, service learning, and independent studies. Advised graduate students, participate on LIS and College committees, and serve on doctoral student dissertation committees. Oversaw and facilitated the LIS graduate student association and alumni association.
- 2000-2002** **Affiliate Faculty, Library & Information Science, College of Education, University of Denver (Colorado).** Served as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), “core courses,” and special topics. Oversaw and facilitated the LIS graduate student association and alumni association.
- 2000-2001** **Special Assistant to the Secretary’s Regional Representative, U.S. Department of Education, Region VIII, Denver, Colorado.** Served as the principal advisor and representative of the U. S. Secretary of Education’s Regional Representative (SRR). Ensured the implementation of major goals of the SRR and the Secretary. Provided leadership on behalf of the SRR in contacts with high-level officials in Region VIII requiring sensitive policy interpretation in communication with senior Department officials to solve problems and resolve issues raised by State and local education officials. Served as the primary contact for School-to-Work/Career, Children’s Health Insurance Program, and Safe and Drug-Free Schools. Delivered technical assistance to local education agencies and institutions of higher education in technology, professional development, and school construction.
- 1999-2000** **Catalog Librarian, Jefferson County Public Library, Lakewood, Colorado.** Performed original, copy cataloging and classification of library materials (English and Spanish) using standard library protocols; completed original descriptive cataloging and subject analysis; enhanced brief catalog and authority records in III.
- 1997-1999** **Development Officer, McREL International, Aurora, Colorado.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for educational agencies. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.
- 1995-1997** **Education Specialist, Education Service Center, Region One, Edinburg, Texas.** Served as member of Administrative Cabinet team in strategic planning, development of proposals and contracts, implementation, and evaluation of telecommunications capabilities, services, products, and programs for 40 school districts serving 283,000 students in 7 counties. Provided creative leadership to regional and state committees to solicit ideas, identify strategic goals and objectives, plan, develop, present, and evaluate funding opportunities and professional development for 400 librarians.

- 1993-1996** **Assistant Professor of Library Science, Sam Houston State University, Huntsville, Texas.** Served as a faculty member teaching 400 graduate students in technical services (cataloging, bibliographic control, classification), automation, and networking. Participated in distance education program and coordinated annual conference. Conducted university and Texas Library Association-funded field research focused on library collection development and academic achievement.
- 1992-1993** **Head Librarian, Rocky Mountain College of Art & Design, Denver, Colorado.** Responsible for the daily operation, selection and acquisition of materials, formulation of policies for library operations, media center, and photography/slides archives. Designed and implemented library automation and delivery of electronic resources to college community.
- 1981-1985** **Development Officer, PRLC, Inc., Pittsburgh, Pennsylvania.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for 100 institutional member organizations. Coordinated the development of proposals and contracts totaling \$4,000,000 annually. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.
- 1981** **Director of Library Development, Pennsylvania Department of Education, Harrisburg, Pennsylvania.** Responsible for statewide development, technical assistance, professional development, resource sharing, children's services, institutional library services, networking, and state aid program for all libraries throughout the Commonwealth. Functioned as liaison to Governor's Advisory Council, LSCA Advisory Council, District Administrators, private colleges, universities, consortia managers, and network directors. Supervised \$14,000,000 formula-based state aid program and \$3,000,000 grant awards to individual libraries, consortia, and networks.
- 1978-1981** **Assistant Director, Southern Tier Library System, Corning, New York.** Coordinated operation of system-wide programs (technical assistance, professional development, resource sharing, technical services, outreach) to 40 public libraries in 5 counties serving 500,000 residents. Solicited ideas, identified goals, sponsored, and evaluated professional development opportunities and technical assistance sessions.
- 1976-1978** **Division Librarian for Technical Services, Corpus Christi Public Libraries, Corpus Christi, Texas.** Provided leadership in acquisitions, cataloging, serials control, and processing for main library and 4 branches serving 250,000 residents. Participated as senior member of library management team. Compiled and prepared technical evaluations, reports, and statistical analyses of Division operations to measure the achievement and cost of annual goals, objectives, and staff performance.
- 1975-1976** **System Coordinator, San Antonio Major Resource Center, San Antonio, Texas.** Served as senior member of the management team for District X Office, charged to provide technical assistance, resource sharing, media services, and professional development to librarians and staff representing 30 public library jurisdictions in 21 counties serving 1,500,000 residents. Functioned as liaison to System Director, staff, and members of governing bodies with the System Board of Directors and the Texas State Library and Historical Commission. Prepared LSCA grant applications and monitored awards totaling \$1,100,000 annually.

- 1973-1975** **Bilingual Branch Librarian, San Antonio Public Library, San Antonio, Texas.** Worked as librarian providing reference, information, and readers' advisory services in branch serving 50,000 Spanish-speaking residents in southwest San Antonio. Participated in collection development and resource acquisition activities, specializing in children's work, Spanish language resources, and multicultural studies.
- 1972-1973** **Librarian, Holding Institute, Laredo, Texas.** Worked as high school librarian serving 500 boarding students in Spanish-speaking environment of private school. Provided reference, research assistance, and library instruction to students and 35 faculty members.
- 1966-1971** **Rockford Public Library, Rockford, Illinois.** Worked in branches as part-time as a Library Assistant, Clerk, and Page in city library serving 150,000 residents.

PUBLICATIONS

Editor-reviewed Monographs (Completed and in Progress)

Hall-Ellis, Sylvia D., and Mary Bolin. *Contemporary Cataloging in an RDA Environment: A Handbook for Students and Practitioners*. Chicago, IL: American Library Association. Under contract & In development.

RDA Testing: Lessons Learned and Challenges Revealed. Sylvia D. Hall-Ellis and Robert O. Ellett, Jr., eds. Binghamton, N.Y.: Haworth, 2012. 128 p.

Hall-Ellis, Sylvia D., Stacey L. Bowers, Christopher D. Hudson, and M. Claire Williamson. *Librarian's Handbook for Seeking, Writing, and Managing Grants*. Santa Barbara, Calif.: Libraries Unlimited, 2011. 315 p.

Hall-Ellis, Sylvia D., with Ann Jerabek, and Merrie W. Valliant. *Contemporary Cataloging: A Handbook for Practitioners and Students*. Open access text. Athens, GA: University of Georgia System Regents, 2011. 767 p.

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Hall-Ellis, Sylvia D. "The Relationship of Situational Leadership and the Dreyfus Model of Skill Acquisition for Supervisors in Cataloging and Metadata Services." To be submitted to *Library Resources and Technical Services*. In progress.

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Faculty Voices: Testimonials from the Frontiers of a Development Education Redesign. Elaine DeLott Baker, Marilyn Smith, and Sylvia D. Hall-Ellis, eds. Denver, Colo.: Colorado Community College System, 2014.

Lewis, Melanie, Jamie M. Van Leeuwen, and Sylvia D. Hall-Ellis. *Project Homeless Connect 7 Event Evaluation*. Denver, Colo.: University of Colorado Denver, 2009.

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- Bruntjen, Scott and Sylvia D. Hall. *South Dakota Library Automation Plan: Final Report*. Pittsburgh, Pa.: PRLC, Inc., 1982. Reprinted by the South Dakota State Library, 1983.
- Bruntjen, Scott and Sylvia D. Hall. *Altoona Automation Plan: Final Report prepared for the Altoona Area Public Library and the Altoona District Library Center*. Pittsburgh, Pa.: PRLC, 1983.
- Bruntjen, Scott, Sylvia D. Hall and Paul J. Pugliese. *College Space Utilization Study*. Pittsburgh, Pa.: PRLC, Inc., 1983.
- Hall, Sylvia D. *Pennsylvania Public Library Film Center Union Catalog Cataloging and Technical Services Procedures Manual*. Pittsburgh, Pa.: PRLC, Inc., 1982.
- Hall, Sylvia D. *History of Library Development in Pennsylvania: A Review and Content Analysis of the Plans, 1955-1980*. Pittsburgh, Pa.: PRLC, Inc., 1982.
- Hall, Sylvia D. *Newspapers on Microfilm: A Listing of Newspapers in Allegheny, Chemung, Schuylers, Steuben, and Yates Counties*. Ithaca, N.Y.: South Central Reference and Research Council, 1981.
- Hall, Sylvia D. *OCLC/ILL Subsystem at Southern Tier Library System*. Albany, N.Y.: SUNY/OCLC Network, 1980.
- Hall, Sylvia D. *Retrospective Conversion for Major Public Libraries in South Central New York State: A Technical Report*. 2 vols. Corning, N.Y.: Southern Tier Library System, 1979-1980.
- Hall, Sylvia D. *The Librarian and the Mexican-American Patron in Texas*. Austin, Tex.: Texas State Library, 1978.

Other Publications

- Hall-Ellis, Sylvia D., ed. *Library and Information Science Program Self-Study Document for Accreditation by the American Library Association*. St. Paul, MN: St. Catherine University, 2017. 255 p.
- Hall-Ellis, Sylvia D., and Robert O. Ellett, Jr., guest editors. *RDA Testing: Lessons Learned and Challenges Revealed: A Special Issue of Cataloging & Classification Quarterly* 49, no. 7-8 (November 2011).
- Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Fundamentals of Cataloging I: An Online ALCTS Course*. Chicago, Ill.: American Library Association, 2009.
- Hall-Ellis, Sylvia D., Angela J. Kinney and Martha Ann Bace, editors. *Best Practices in Cataloging Education Identified at the 2007 ALCTS Pre-conference: A Special Issue of the Journal for Library and Information Science Education* 49, no. 2 (Spring 2008).

- Hall-Ellis, Sylvia D. *Cataloging Education: A New Emphasis for the Library and Information Science Curriculum*. Presentation delivered to the ALCTS Pre-conference, 132nd Annual Conference, American Library Association, Washington, D.C., June 22, 2007. <http://www.loc.gov/aba/professional/>
- Hall-Ellis, Sylvia D. “*Cataloger Competencies: Do the Employers Require What the Professors Teach?*” Presentation delivered to the ALCTS CCS Heads of Cataloging Discussion Group, 131st Annual Conference, American Library Association, New Orleans, Louisiana, June 26, 2006. <http://dlist.sir.arizona.edu/>
- Hall-Ellis, Sylvia D., guest editor, with Deborah S. Grealy, Clara L. Sitter, and Tassos Petrou. *Library Students’ Voices in Colorado: An Issue of Colorado Libraries* 31:1 (Spring 2005).
- Hall-Ellis, Sylvia D., ed. *Library and Information Science Program Self-Study Document for Accreditation by the American Library Association*. Denver, Colo.: University of Denver, College of Education, 2003. 125 p. with CD-ROM.
- Hall-Ellis, Sylvia D. and Deborah S. Grealy, guest editors. *Library Education in Colorado: An Issue of Colorado Libraries* 29, no. 2 (Summer 2003).
- Hall-Ellis, Sylvia D., ed. *Library and Information Science Program Self-Study Document for Accreditation by the American Library Association*. Denver, Colo.: University of Denver, College of Education, 2003.
- Hall-Ellis, Sylvia D. “Adaptive Furniture for the ADA-Qualified: An Investigative Study.” 2001. Unpublished manuscript.
- Hall-Ellis, Sylvia D. “Cataloging Electronic Serials: A Study in User Access and Article Delivery.” 2001. Unpublished manuscript.
- Hall-Ellis, Sylvia D. “E-books: Acquisition and Circulation Issues in Public Libraries.” 2001. Unpublished manuscript.
- Hall-Ellis, Sylvia D. “Authority Control and Its Importance in School Library Media Online Catalogs.” 1999. Unpublished manuscript.
- Hall, Sylvia D. “Cooperation Improving Service in San Antonio System.” *Texas Libraries* XXXVII (Spring 1976): 27-29.
- Hall, Sylvia D. “Summer is Sea Monstrously Fun!” *Texas Library Journal* L (December 1974): 224-226.
- Hall, Sylvia D. “A Brief Annotated Bibliography of Non-book Materials on the Mexican American.” *Texas Library Journal* XLVIII (October 1972): 213-232.

Book Reviews

- ALA Book of Library Grant Money*. Ann Kepler, ed. 8th ed. Chicago, IL: American Library Association, 2011. 978-0-8389-1058-0, \$175.00 [*Colorado Libraries*, June 2012]
- Developing a Compensation Plan for Your Library*. Paula M. Singer and Laura L. Francisco, comps. 2nd ed. Chicago, IL: American Library Association, 2009. 978-0-8389-0985-0, \$57.00 [*Colorado Libraries*, March 2012]
- Frugal Librarian*. Carol Smallwood, ed. Chicago, IL: American Library Association, 2011. 978-0-83891-075-7, \$42.00 [*Colorado Libraries*, February 2012]

- Dowlin, Ken. *Getting the Money: How to Succeed in Fundraising for Public and Nonprofit Libraries*. Westport, Conn.: Libraries Unlimited, 2008. 978-1-59158-597-X, \$50.00 [*Colorado Libraries*, February 2009]
- Lundahl, Mats. *Bebo de Cuba; Bebo Valdés y Su Mundo*, by Mats Lundahl. Traducción de Linda Oakeshott Dragó. Barcelona: RBA Libros, 2008. 978-849-86-7259-6, \$33.99 [*Críticas*, November 2008]
- Bonelli, Florencia. *Marlene*, by Florencia Bonelli. Buenos Aires: Aguilar, Altea, Taurus, Alfaguara, 2008. 978-987-04-0995-3, \$24.95 [*Críticas*, October 2008]
- Keret, Etgar. Traducción de Ana María Bejarano. *Pizzería Kamikaze y Otras Relatos*. México, D.F.: Editorial Sexto Piso, 2008. 968-5679-29-0, no price given [*Críticas*, September 2008]
- Littauer, Marita, and Florence Littauer. *Enriquece tu Comunicación. Miami, Fla.: Editorial Unilit, 2008. 978-0-7899-1521-4, \$11.99 [*Críticas*, August 2008]*
- Martínez, Guillermo. *La Muerte Lenta de Luciana B.* New York: Rayo Planeta, 2008. 978-0-06-156551-9, \$14.95 [*Críticas*, May 2008]
- Matthews, Joseph R. *The Evaluation and Measurement of Library Services*. Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-532-9, \$50.00 [*Colorado Libraries*, April 2008]
- Gómez-Jurado, Juan. *A Masacre de Virginia Tech: Anatomía de una Mente Torturada*. Barcelona: Ediciones El Andén, 2007. 978-84-935789-4-7, €16.50 [*Críticas*, February, 2008]
- Matthews, Joseph R. *Library Assessment in Higher Education*. Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-531-2, \$45.00 [*Colorado Libraries*, February 2008]
- Chacón, Inma. *La Princesa India: Cuando el Viento Azul*. México: Alfaguara, 2006. 970-770398-9, \$19.95 [*Críticas*, June 2006]
- Vargas Llosa, Mario. *Israel/Palestina: Paz o Guerra Santa*. fotogs. by Morgana Vargas Llosa. Spain/U.S.: Aguilar: Santillana, 2006. 84-03-09691-7, paper, \$19.95 [*Críticas*, May 2006]
- Findlay, Diane. *Digging into Dewey*. Fort Atkinson, Wisc.: Upstart Books, 2005. 978-1-932146-18-9, \$16.95 [*Colorado Libraries*, May 2006]
- Pequeñas Resistencias 4: Antología del Nuevo Cuento Norteamericano y Caribeño*. Menéndez, Ronaldo, Ignacio Padilla & Enrique del Risco, eds. Madrid: Páginas de Espuma, 2005. 84-95642-59-X, paper, \$36.95 [*Críticas*, April 2006]
- Rueda, André. *Vengo a Salvar a España: Biografía de Un Franco Desconocido*. Madrid: Nowtilus (Investigación Abierta), 2005. photogs., bibliog. 84-9763-202-8, paper, \$23.95 [*Críticas*, March 2006]
- Becerra, Ángela. *El Penúltimo Sueño*. 1st ed. Barcelona: Planeta, 2005. 84-08-05795-2, \$25.95. [*Críticas*, January 2006]
- Aguilar Camín, Héctor. *La Conspiración de la Fortuna*. 1st ed. México: Planeta, 2005. 970-37-0368-2, \$19.95 [*Críticas*, October 2005]
- México en Sus Libros*. Enrique Florescano with Pablo Mijangos, editors & compilers. 1st ed. México, D.F.: Taurus Aguilar, 2004. 968-19-0783-3, \$16.95 [*Críticas*, September 2005]

- Historia Económica de México*. Coordinator, Enrique Semo. México: Universidad Nacional Autónoma de México, Editorial Oceano de México, 2004. 13 vols. 970-32-0805+3 (obra completa), \$9.25 each [*Críticas*, August 2005]
- Czarnowsky, Christyne A. and Michael H. Williams. *Managing Your Wired Workforce: A Practical Guide*. Denver, Colo.: Bradford Pub., 2003. 1-883726-79-4, \$24.95 [*Colorado Libraries*, 2004]
- Abraham Lincoln*. Colección Grandes Biografías. Madrid: Edimat Libros, 2003. 84-8403-858-0, €4.95 [*Críticas*, 2004]
- Alponte, Juan María. *Colón: el Hombre, el Navegante, la Leyenda*. México, D.F.: Aguilar, 2003. 968-19-1260-8, \$16.95 [*Críticas*, 2004]
- Olcese Salvatecci, Alfieri. *Cómo Estudiar con Éxito: Técnicas y Hábitos Para Aprender Mejor*. México, D.F.: Alfaomega Grupo Editor, 2002. 970-15-0764-9 [*Críticas*, 2003]
- Mujeres Como Islas: Antología de Narradoras Cubanas, Dominicanas, Puertorriqueñas*. Edición: Olga Marta Pérez, Thelma Jiménez, Andrés Blanco D., eds. Santo Domingo, República Dominicana: Ediciones Ferilibro, 2002. 959-209-419-5 [*Críticas*, 2003]
- Tibol, Raquel. *Los Murales de Diego Rivera: Universidad Autónoma Chapingo*. México, D.F.: Editorial RM, Universidad Autónoma Chapingo, 2002. 968-5208-08-5 [*Críticas*, 2003]
- Lindsay-Poland, John. *Emperors in the Jungle: the Hidden History of the U.S. in Panama*. Durham, N.C.: Duke University Press, 2003. 0-8223-3098-9, \$18.95 [*Críticas*, 2003]
- Kaplan, Allison G. and Ann Marlowe Riedling. *Catalog It! A Guide to Cataloging School Library Materials*. Worthington, Ohio: Linworth Pub., 2002. 1-58683-014-7, \$44.95 [*Colorado Libraries*, 2002]
- Bardach, Ann Louise. *Cuba Confidential: Love and Vengeance in Miami and Havana*. New York: Random, 2002. 0-375-50489-3, \$25.95 [*Library Journal*, 2002]
- Swan, James. *Fundraising for Libraries: 25 Proven Ways to Get More Money for Your Library*. New York: Neal Schuman, 2002. 1-55570-433-6, \$69.95 [*Colorado Libraries*, 2002]
- Puig de Lange, Victoria. *Sol Con Agua*. Nashville, Tenn.: Editorial Vistazo/Ediciones Reio Negro, 2002. 0-9724506-0-2, \$17.75 [*Críticas*, 2002]
- The Encyclopedia of Latin American Politics*. Edited by Diana Kapiszewski; assistant editor, Alexander Kazan. Westport, Conn.: Oryx Press, 2002. 1-57356-306-4, \$74.95 [*Library Journal*, 2002]
- Vargas Lizano, Isabel. *Y Si Quieres Saber de Mi Pasado*. Con la colaboración de J.C. Vales. Madrid: Santillana Ediciones Generales, S.L., 2002. 84-03-09278-4, \$18.95 [*Críticas*, 2002]
- Ruy Sánchez, Alberto. *Los Jardines Secretos de Mogador: Voces de Tierra*. México, D.F.: Alfaguara, S.A., 2001. 968-19-0879-1, \$16.95 [*Críticas*, 2002]
- Chávez, Ricardo and Celso Santajuliana. *El Final de las Nubes*. Barcelona: RBA Libros, S.A., 2001. 84-7901-760-0, \$11.95 [*Críticas*, 2002]

The Power of Language / El Poder de la Palabra: Selected Papers from the Second REFORMA National Conference. Edited by Lillian Castillo-Speed and the REFORMA National Conference Publications Committee. Englewood, Colo.: Libraries Unlimited, 2001. 1-563089459, \$35.00 [*Colorado Libraries*, 2001]

Martínez, Rubén. *Crossing Over: A Mexican Family on the Migrant Trail.* Metropolitan: Holt, 2001. 0-8050-4908-8, \$26.00 [*Library Journal*, 2001]

Guevara, Ernesto "Che." *The African Dream: the Diaries of the Revolutionary War in the Congo.* Translated from the Spanish by Patrick Camiller. With an introduction by Richard Gott and a foreword by Aleida Guevara March. New York: Grove Press, 2001. 0-8021-3834-9, \$13.00 [*Library Journal*, 2001]

Cooper, Gail and Garry Cooper. *New Virtual Field Trips.* Englewood, Colo.: Libraries Unlimited, 2001. 1-56308-887-8, \$27.50 [*Colorado Libraries*, 2001]

NATIONAL SERVICE & PROFESSIONAL AFFILIATIONS

American Library Association, Life Member

Association for Library Collections & Technical Services (now CORE)

Cataloging, Classification, and Metadata Section

Margaret Mann Citation Committee, 2023-

ALCTS Editorial Board, Member, 2015-2019

Committee on Cataloging: Description and Access, Member, 2008-2012

Test Site for RDA, Manager, 2009-2011

Nominating Committee, Member, 2007-2008

Committee for Education and Training of Catalogers, Chair, 2006-2007, Member, 2003-2007

Competencies & Education for a Career in Cataloging Interest Group, Chair, 2010-2012; Member, 2010-

President's Program Committee, 2015-2016

Education Committee, Member, 2005-2007

Task Force on Competencies and Education for a Career in Cataloging, Chair, 2007-2009

2007 Annual Meeting Pre-conference, "What They Don't Teach in Library School: Competencies,

Education and Employer Expectations for a Career in Cataloging," Steering Committee Chair

Fundraising Committee, Member, 2004-2006

Office of Diversity

Committee on Diversity, Chair, 2010-2011

Diversity Research Advisory Committee, Member, 2009-2010

Spectrum Scholar Mentor, 2009

Diversity Grants Review Committee, Member, 2007, 2010, 2012

Office of Statistics and Research

Research and Statistics Committee, Member, 2005-2007; Intern, 2003-2005

Library Research Round Table

Nominating Committee, 2022-2023

Membership Committee, 2019-2021

Board of Directors, Member At-Large, 2009-2012

Office of Accreditation

Accreditation Panel Member (training completed 2004)

Accreditation Review Panel Member (training completed 2004)

REFORMA, Life Member

National Board of Directors, 2005-2013

National Fundraising Chair, 2005-2013

National Recruiting and Mentoring Committee, 2008-2010

Colorado Chapter, Secretary, 2004-2005

Colorado Chapter Liaison to National Board of Directors, 2004-2013

American Association of Law Libraries (AALL), Life Member Online Audiovisual Catalogers Association (OLAC) Colorado Association of Law Librarians (CoALL)

American Association of University Women Association for Library and Information Science Education (ALISE)

University of Denver ALISE Representative, 2003-2008; 2010-2011

Membership Advisory Committee, 2007-2010

Technical Services Education Special Interest Group, 2003-

Garfield Doctoral Dissertation Award Reviewer, 2012

Garfield Doctoral Dissertation Scholarship Reviewer, 2014

American Association of University Professors (AAUP), 2006-

American Grant Writers Association, 2014- Grant Professionals Institute, 2016- National Grants Management Association, 2014-

Grant Reviewer (National and Regional Team Leader), U.S. Department of Education, 1998- Grant Reviewer, Broadband Technologies Opportunity Program, U.S. Department of Commerce, 2009
Grant Reviewer, Institute of Museum and Library Services, 1998-2000
Grant Reviewer, Colorado Department of Education, 2014-
Grant Reviewer, Colorado State Library, 1998-
Grant Reviewer, American Association of Community Colleges *Working Connections* program, 1999
Peer Reviewer, *Journal for Library and Information Science Education*, 2005-
Peer Reviewer, *Journal of Library Metadata*, 2009
Peer Reviewer, *International Journal of Library and Information Science*, 2011
Regular Columnist, *The Bottom Line*, 2013-2016
Book Reviewer, *Library Journal*, 2001
Book Reviewer, *Criticas*, 2002-2009
Book Reviewer, *Colorado Libraries*, 2000-2012

REGIONAL SERVICE & PROFESSIONAL AFFILIATIONS

Mountain Plains Library Association

Professional Development Grants Committee, Member, 2005-2006
Professional Development Policy and Guidelines Sub-committee Chair, 2006

Colorado Association of Libraries

“Student Voices” Column Editor, *Colorado Libraries*, 2005-2006
Conference Planning Committee, Member, 2002
Technical Services and Automation Division, Chair, 2002-2003; Member, 2000-
Academic Libraries Division, Peer Review Conference Papers Committee, Member, 2007-2009
Education Committee, Member, 1988-1993
Diverse Populations Committee, Member, 2009-2013

SERVICE TO THE UNIVERSITY OF DENVER

Center for Teaching and Learning Faculty Advisory Board, 2007-2008; 2010-2012
Center for Community Engagement and Service Learning Advisory Board, 2007-2012
Faculty Senate
Executive Committee, 2008-2013
Nominations, Rules & Credentials Committee, Chair, 2008-2013; Member 2007-2013
Appointment, Promotion, and Tenure Revision Committee, 2010-2012
Grievance Policy Committee Member, 2007-2010
Law Library Director Search Committee Chair, 2012-2013
PROF Grant Review, College Representative to the University Review Team, 2006, 2008
Project Homeless Connect Evaluations, Principal Investigator, 2006-2009
University Technology Council, 2007-2009
University of Denver Hyde Interviews for Incoming Freshmen, 2003-2012

SERVICE TO THE MORGRIDGE COLLEGE OF EDUCATION

Appointment, Tenure & Review Committee
Member, voting, 2003-2005; 2007- 2009
Chair, Clinical Faculty Promotion & Tenure Policy Subcommittee, 2008-2009
Member, Community Engagement Subcommittee, 2007-2009
Member, Tenure Review Panel, 2003
Advancement and Alumni Relations Committee, Chair, 2003-2007; Member, 2002-2007
College Building Committee Member, 2004-2010

College of Education Student Association, Faculty Advisor, 2004-2007; 2009-2010
Faculty Senator, 2007-2013
Research and Scholarship Committee, Chair, 2008-2009; Member, 2002-2003, 2008-2009
Research and Grant Mentoring Committee, Chair, 2009-2010
Research Task Force Member, 2010-2012
Search Committee Member, Assistant Professor for Curriculum & Instruction, 2010-2011
Workload Task Force Member, 2010-2011

SERVICE TO THE LIBRARY & INFORMATION SCIENCE PROGRAM

Library and Information Science Student and Alumni Association, Faculty Advisor, 2002-2008
ALA Student Chapter, Faculty Advisor, 2005-2008
Beta Phi Mu Phi Chapter, Faculty Advisor, 2004-2014
Steering Committee Member, Accreditation by the American Library Association, 2001-2004
Search Committee Member, Associate Professor for LIS, 2006
Search Committee Chair, Assistant Professors for LIS, 2003, 2005, 2006, 2007
Search Committee Ex-Officio Member, Director for LIS, 2004

SERVICE TO SAM HOUSTON STATE UNIVERSITY

Rio Roundup: South Texas Literature Conference, Conference Coordinator, 1993
External Relations, Fund Raising, Grants Committee, Chair, 1993-1995
Advisory Council Committee, Chair, 1993-1995
Students, Admissions, and Advisement Committee, Chair, 1994
Institutional Effectiveness Committee, Member, 1993-1995

SERVICE TO THE COLLEGE OF EDUCATION AND APPLIED SCIENCE

Faculty Affairs Committee, Member, 1993-1995
Curriculum Committee, Member, 1993-1995
Continuing Education Committee, Member, 1993-1995

SERVICE TO THE COMMUNITY

French Teacher & Student Exchange with Laon, France, Monarch High School, Boulder Valley School District (Boulder, Colorado), 2017-
Denver/Boulder Games 2022, Board of Directors, Secretary-Treasurer, 2015-2018
United Way Campaign Committee, College of Education, 2006
Arapahoe County, Election Judge for the County Clerk and Recorder, 2000-2005
Arthritis Foundation, Rocky Mountain Chapter, Certified Educator & Trainer, 1999-2008
Bonfils Blood Center, Silver Level Donor, 2000-2016
Denver Museum of Natural History, Docent, 1992
Tech Prep of the Lower Rio Grande Valley, Inc. (Harlingen, Texas) Board of Directors, 1995-1997
Executive Committee, 1996-1997; Chair, Development Committee, 1995-1997; Chair, Fiscal Agency Committee, 1995-1996; Chair, Colleges and Universities Committee, 1996-1997
Gilpin County (Colorado) Public Library Board of Trustees, 1986-1989; Vice President, 1987-1989
City of Central (Colorado) Economic Development Committee, 1987-1989
Columbine Family Health Centers, Inc. (Nederland and Black Hawk, Colorado) Board of Directors, 1988-1989

CERTIFICATION

Permanent Public Librarian Certificate - Pennsylvania, New York, Texas
Westlaw Expert Witness, 2008-
Certified Grant Writer®, 2016-

AWARDS AND HONORS

Advanced Practitioner for Service Learning and Community Engagement, University of Denver, 2011
 Platinum Star Alumnae, College of Information, Library Science & Technologies, University of North Texas, 2009
 Commendation for Integration of Technologies in Teaching & Learning Environment, University of Denver, 2006
 Outstanding Adjunct Faculty Member Award, College of Education, University of Denver, 2002
 Beta Phi Mu, Pi, University of Pittsburgh, 1985
 Alpha Lambda Sigma, University of North Texas, 1972
Albert Nelson Marquis Lifetime Achievement Award, Who's Who in America
Who's Who in American Women
Who's Who of Women Executives
Dictionary of International Biography
Who's Who in the East
Who's Who in the South and Southwest
Who's Who in the World
Who's Who of Online Professionals
Who's Who in Library and Information Science
2,000 Notable Women
Who's Who of Emerging Leaders
Who's Who in Professional and Executive Women
Who's Who in American Education
International Who's Who of Professional and Business Women
International Leaders in Achievement
International Educator of the Year
Who's Who in Finance and Industry
Who's Who in Finance and Business

Invited International and National Conference Presentations

Hall-Ellis, Sylvia D. *Presentation of the Robert O. Ellett Endowed Scholarship*. Presentation delivered to the School of Information at San Jose State University Alumni & Student Program, American Library Annal Conference, San Diego, Calif., June 29, 2024.

Driscoll, Margaret, Christy Confetti Higgins, Scott Brown, and Sylvia D. Hall-Ellis. *A View from Within: Open House Tour of Three Canvas Core Courses*. Presentation to be delivered at the School of Information, San José State University Professional Development Seminar, San José, California, October 17, 2019.

Hall-Ellis, Sylvia D. *Invest in Me -- I'm Your Future: Succession Planning for Libraries*. Keynote presentation delivered at the ALCTS President's Symposium, Boston, Mass., January 8, 2016.

Seidel, Kent E. and Sylvia D. Hall-Ellis. *Making Grants Work for You: Strategies for Doctoral Students and Early Career Scholars*. Presentation delivered at the University Council for Educational Administration, Early Career Scholars Session, Indianapolis, Ind., November 9, 2013.

Hall-Ellis, Sylvia D. *So You Want to be a Manager; Leadership Skills and Competencies for Technical Services Managers and Administrators*. Presentation delivered at the 138th Annual Conference, American Library Association, Chicago, Ill., June 29, 2013.

Seidel, Kent E., Karen S. Riley, Lyndsay Agans, Susan Korach, and Sylvia D. Hall-Ellis. *Making Grants Work for You (Instead of Just Working for Grants)*. A panel discussion delivered at the University Council for Educational Administration, Early Career Scholars Session, Denver, Colo., November 17, 2012.

Hall-Ellis, Sylvia D. *After the Great TS Reorganization: The Westminster Law Library*. Presentation delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 23, 2012.

Hall-Ellis, Sylvia D. *Conversations with Catalogers in the 21st Century*. A panel discussion sponsored by the ALCTS Competencies for a Career in Cataloging Interest Group, delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 22, 2012.

Hall-Ellis, Sylvia D., moderator. *Mid-Career Leaders Program*. A panel discussion sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 26, 2011.

Hall-Ellis, Sylvia D., moderator. *Diversity Town Hall*. A community conversation sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 24, 2011.

LaBarre, Kathryn, Sylvia D. Hall-Ellis, Karen Anderson, Rick Hasenyager, Christopher Cronin, and Penny Baker. *Briefings from RDA Test Participants*. A panel discussion delivered at the Midwinter Conference, American Library Association, San Diego, Calif., January 7, 2011.

Miksa, Shawne, Marjorie Bloss, and Sylvia D. Hall-Ellis. *Educating the Next Generation of Catalogers: Teaching RDA*. A panel discussion delivered at the 97th Annual Conference, Association for Library and Information Science Education, San Diego, Calif., January 7, 2011.

Hall-Ellis, Sylvia D., Robert Maxwell, John Hostage, and George Prager. *RDA Panel: What Cataloging Managers Need to Know*. Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 12, 2010.

Hall-Ellis, Sylvia D. and Stacey L. Bowers. *Catalogers in the RDA Environment: Skill Sets, Expectations and Challenges*. Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 11, 2010.

Hall-Ellis, Sylvia D. *Comfortable in Your Cataloging and Metadata Specialist Skin? Or, So You Want to Hire a Cataloger*. Presentation delivered to the ALCTS Research Group at the 134th Annual Conference, American Library Association, Chicago, Ill., July 11, 2009.

Perez, Megan, Sylvia D. Hall-Ellis, and Denise Anthony. *From Novice to Expert: Collaboration for Succession Planning*. A “hot topic” presentation delivered at the 14th ACRL Conference, Seattle, Wash., March 13, 2009.

Hall-Ellis, Sylvia D. *Cataloging in the RDA Environment: Skill Sets, Expectations and Challenges*. Presentation delivered to the ALCTS Research and Publications Committee at the Midwinter Conference, American Library Association, Denver, Colo., January 24, 2009.

Hall-Ellis, Sylvia D. *LIS Cataloging Education for the 21st Century: Expectations and Challenges*. A panel discussion held at the 95th Annual Conference, Association for Library and Information Science Education, Denver, Colo., January 23, 2009.

Chu, Clara, Sylvia D. Hall-Ellis, and Mark Winston. *The Doctoral Degree & Building a Career*. A panel discussion delivered at the ALA Office of Diversity Spectrum Doctoral Fellows E.J. Josey Leadership Institute, Midwinter Conference, American Library Association, Denver, Colo., January 20, 2009.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Fundamentals of Cataloging Course: An Overview of the ALCTS Online Course*. Presentation delivered to the ALCTS Big Heads Group, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 30, 2008.

Hall-Ellis, Sylvia D. *Employers' Expectations for Technical Services Librarians: What We Don't Know*. Presentation delivered to the ALCTS Research and Publications Committee Program, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 28, 2008.

Hall-Ellis, Sylvia D., Virginia R. Maloney, and Mary Stansbury. *Institutional Responses to Engaged Scholarship: The Carnegie Foundation Engaged University Classification at Two Universities*. Presentation delivered to the 94th Annual Conference, Association for Library and Information Science Education, Philadelphia, Pa., January 11, 2008.

Hall-Ellis, Sylvia D. *Puzzles, Problems, and Predicaments*. Presentation delivered to the ALCTS Research Discussion Group, 132nd Annual Conference, American Library Association, Washington, D.C., June 23, 2007.

Hall-Ellis, Sylvia D. *Cataloging Education: A New Emphasis for the Library and Information Science Curriculum*. Presentation delivered to the ALCTS Pre-conference, 132nd Annual Conference, American Library Association, Washington, D.C., June 22, 2007. <http://www.loc.gov/catdir/cpsocareercat.html>

Ellett, Jr., Robert O. and Sylvia D. Hall-Ellis. *Copy Cataloging Done Smarter*. Presentation delivered to the International Conference on Interdisciplinary Information Sciences and Technologies (InSciT2006), October 25-28, 2006.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Challenges and Opportunities for Defense Libraries*. Presentation delivered to the 1st Annual Conference of Defense Libraries, Spanish Ministry of Defense, Madrid, Spain, July 7, 2006.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation delivered to the ALCTS CCS Heads of Cataloging Discussion Group, 131st Annual Conference, American Library Association, New Orleans, La., June 26, 2006.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *From Research to Practice: The Scholarship of Teaching and Learning in LIS Education*. Presentation delivered to the at the 92nd Annual Conference, Association for Library and Information Science Education, San Antonio, Tex., January 18, 2006.

Hall-Ellis, Sylvia D. *Employers' Expectations for Entry-Level Catalogers: What Position Announcement Data Indicate*. Research paper delivered to the Technical Services Special Interests Group, 91st Annual Conference, Association for Library and Information Science Education, Boston, Mass., January 12, 2005.
<http://dlist.sir.arizona.edu/>

Hall-Ellis, Sylvia D. *Common Errors in MARC Records Prepared by LIS Students: What Does It Mean?* Research paper delivered to the ALCTS CCS Cataloging Norms Discussion Group, Mid-Winter Conference, 90th American Library Association, San Diego, Calif., January 10, 2004.

Hall-Ellis, Sylvia D. *Visual Arts as Foundation for Successful Library Automation: The Rocky Mountain College of Art & Design Experience*. Paper delivered at the 6th Annual Conference of Higher Education, Charleston, S. C., 1993.

Hall, Sylvia D. *Design Elements for Bibliographic Databases: An Overview*. Paper delivered at the 14th Online National Conference, New York, 1983.

Invited Regional Conference Presentations

- Hall-Ellis, Sylvia D., Hudson, Christopher D., Brittany Cronin, and Kathryn Michaels. "The Colorado Law Project: Meeting the Public's Need for Legal Information." Panel discussion delivered at the Mountain Plains Library Association Conference, Billings, Mont., April 9, 2011.
- Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Education for Information Professionals in New Mexico: Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the New Mexico Library Education Summit, Las Vegas, N.M., September 26, 2005.
- Hall-Ellis, Sylvia D. *Public Library-School Library Partnerships*. Presentation delivered at the 3rd Annual Colorado Association of Libraries Conference with the Mountain Plains Library Association, Denver, Colo., October 22, 2004.
- Hall-Ellis, Sylvia D. *Learn All You Can – Educational Partnership Opportunities for the Lewis and Clark Bicentennial Commemoration*. Paper delivered at the 3rd Annual Lewis and Clark Bicentennial Council National Planning Conference, Bismarck, N.D., April 26, 1998.

Invited State Conference Presentations

- Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Academic Library Leadership Changes: Using Succession Planning and Mentoring*. Presentation delivered at the Minnesota Library Education Conference, St. Cloud, Minn., October 10, 2013.
- Hall-Ellis, Sylvia D., Merrie Valliant, and Melissa Powell. *RDA: What Is It and What Do You Need To Do With It At Your Library?* Presentation delivered at the Colorado Library Consortium Spring Conference, Ft. Morgan, Colo., April 26, 2013.
- Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 4th LEADS Scholars Orientation, Denver, Colo., August 5, 2009.
- Hall-Ellis, Sylvia D. *Service Learning: Enhancement to Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 3rd LEADS Scholars Orientation, Denver, Colo., June 2008.
- Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation*. Sponsored by the Colorado Association of Law Libraries. Paper delivered at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.
- Hall-Ellis, Sylvia D. *Opportunities and Challenges in Law Librarianship: A Community Conversation*. Presentation delivered at the Sturm College of Law, Denver, Colo., November 7, 2007.
- Ellis, Sylvia D. *Grant Writing Resources for Nursing Professionals*. Presentation delivered at the Presbyterian / St. Luke's Health One Medical Center 1st Annual Research Symposium, Denver, Colo., October 17, 2007.
- Hall-Ellis, Sylvia D. *Project Homeless Connect 4 Event Evaluation – Insights and Lessons Learned*. Presentation delivered at the Homelessness Research Symposium: What is DU Doing about Homelessness in Denver, Denver, Colo., September 14, 2007.

Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 2nd LEADS Scholars Orientation, Denver, Colo., August 10, 2007.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 15th Spring Mountains and Plains Parapros Conference, Denver, Colo., February 24, 2007.

Hall-Ellis, Sylvia D. *Public Library Service to Spanish-Speaking and Latino Residents in Denver: A Case Study*. Presentation delivered at the 4th Annual Colorado Association of Libraries Conference, Denver, Colo., November 10, 2005.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 14th Annual Mountains and Plains Parapros Conference, Aurora, Colo., July 29, 2005.

Hall-Ellis, Sylvia D. *Educational Opportunities: Library & Information Science Graduate Education at the University of Denver*. Presentation delivered at the 13th Annual Mountains and Plains Parapros Conference, Centennial, Colo., August 6, 2004.

Hall-Ellis, Sylvia D. *Library Education & Training: Focus on the West: An LIS Faculty Member's Personal Response*. Presentation delivered at the 1st Annual Colorado Association of Libraries Conference, Keystone, Colo., October 18, 2002.

Hall-Ellis, Sylvia D. *Grant Writing for School Librarians*. Presentation delivered at the 2002 Annual Colorado Education Media Association Conference, Colorado Springs, Colo., February 15, 2002.

Hall-Ellis, Sylvia D. *Grants – Opportunities for the Future*. Paper delivered at the Southeast Regional Accountability Annual Conference, Lamar, Colo., November 12, 1998.

Hall-Ellis, Sylvia D. *The Texas Library Connection and Interlibrary Loan: An Experiment in Resource Sharing*. Paper delivered at the Texas Computer Educators' Association Annual Conference, Austin, Tex., February 6, 1997.

Hall-Ellis, Sylvia D. *Finding Grant Sources on the Internet: A Guide for Librarians*. Paper delivered at the 2nd Annual Institute for School Library Personnel, Pharr-San Juan-Alamo North High School, Pharr, Tex., July 29, 1996.

Hall-Ellis, Sylvia D. *Mathematical and Logical Thinking: A Critical Intelligence*. Paper delivered at the 3rd Annual Paraprofessional Conference at the University of Texas - Pan American, Edinburg, Tex., March 8, 1996.

Hall-Ellis, Sylvia D. *Cataloging Trends and Issues: Update Session*. Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 19, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: Tips and Encouragement for School Librarians*. Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 18 and 19, 1995.

Hall-Ellis, Sylvia D. *How to Become an Expert Grant Writer*. Paper delivered at the 3rd Annual High School Principals' Academy, South Padre Island, Port Isabel, Tex., June 19, 1995.

Texas Library Study: Results from Regions I and II. Paper delivered at the 3rd Annual Technology Conference, Texas A&M University, College Station, Tex., November 18, 1994.

Hall-Ellis, Sylvia D. *Academic Achievement and Middle School Students*. Paper delivered at the 8th Annual Young Adult Conference, Sam Houston State University, Huntsville, Tex., November 5, 1994.

Hall-Ellis, Sylvia D. *Multimedia Resources for Library Leaders*. Paper delivered at the Institute for Librarians in A Multicultural Environment, Sam Houston State University, Huntsville, Tex., June 10, 1994.

Hall-Ellis, Sylvia D. *Finding the Resource: Empowering the User, or, the Case for Curriculum Based Subject Access to Learning Resource Center Collections*. Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall-Ellis, Sylvia D. and William H. Pichette. *Sam Houston State University Makes Use of OCLC/AMIGOS Collection Analysis CD*. Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall, Sylvia D. *Funding and Library Development in Pennsylvania: A Symbiotic Relationship*. Paper delivered at the Annual Graduate Student Colloquia, University of Pittsburgh, School of Library and Information Science, 1982.

Hall, Sylvia D. *Leadership for Public Library Trustees*. Paper delivered for the Trustees Division, Pennsylvania Library Association Annual Conference, Lancaster, Penn., 1981.

Seminar and Professional Development Presentations

Taylor, Meredith, and Sylvia D. Hall-Ellis. *Talent Management and Succession Planning*. ALCTS eForum, held March 22, 2017.

Hirsh, Sandra, Heather O'Brien, Michelle Holschuh Simmons, Michael Krasulski, and Sylvia D. Hall-Ellis. *Information Services Today: An Introduction. Part 3: Information Services: Roles in the Digital Age*. Rowan and Littlefield in partnership with Library Journal webinar, recorded February 5, 2015.

Hall-Ellis, Sylvia D. and Jennifer Sweda. *Copy Cataloging in an RDA Environment*. ALCTS eForum, held May 14 and 15, 2013.

Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation*. Sponsored by the Colorado Association of Law Libraries, presented at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.

Hall-Ellis, Sylvia D. and Beatrice Z. Gerrish. *Reading and Libraries: Recent Research in Reading*. Presentation at the Ricks Center for Gifted Education, Denver, Colo., March 4, 2008.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation for the School of Library and Information Science, San José State University, February 12, 2008.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Rules, Tools, and Conventions for Building a Multi-institutional Catalog*. Sponsored for the Spanish Ministry of Defense, Madrid, Spain, July 10, 2006.

Hall-Ellis, Sylvia D. *Cash for Kids: Grant Writing Opportunities for Youth Services Librarians*. Sponsored by the Colorado Young Adult Librarians; presented at Bemis Memorial Library, Littleton, Colo., November 13, 2002.

Hall-Ellis, Sylvia D. *MARC Records and Authority Control: Planning for Bibliographic Database Migration*. Sponsored and held at the Douglas County Public Library, Castle Rock, Colo., May 28, 2002.

Grant Writing: A Refresher for Librarians. Sponsored by Library and Information Science Program, College of Education, University of Denver; presented at University Center at Chaparral, August 12, 2000.

Hall-Ellis, Sylvia D. *Shaking the Money Tree – Basic Grant Writing for Colorado Educators*. Sponsored by the Office of Educational Telecommunications of the Colorado Department of Education. Pikes Peak Community College, Colorado Springs, Colo., November 16, 1998.

Pueblo School District 60, Pueblo, Colo., November 12, 1998.
University of Northern Colorado, Greeley, Colo., November 10, 1998.
United Technology Educational Partnership, Grand Junction, Colo., November 9, 1998.

Hall-Ellis, Sylvia D. *Cataloging Multimedia, Kits, Globes and Map Materials in USMARC*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 24, 1997 and December 12, 1996.

Hall-Ellis, Sylvia D. *New Standards for School Library Media Centers*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 15, 1997.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future*. Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., April 4, 1997.

Hall-Ellis, Sylvia D. *Cataloging Sound Recordings and Audio Materials in USMARC*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 20, 1997 and November 21, 1996.

Hall-Ellis, Sylvia D. *Evaluating and Selecting CD-ROMs for School Library Media Collections*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 18, 1997.

Hall-Ellis, Sylvia D. *Cataloging Audiovisual Materials in USMARC*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 27, 1997, November 7, 1996 and October 24, 1996.

Hall-Ellis, Sylvia D. *Introduction to Dialog: Basic Searching Strategies*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 14, 1997.

Hall-Ellis, Sylvia D. *Cataloging Books in USMARC*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 30, 1997, October 10, 1996, September 26, 1996 and August 8, 1996.

Hall-Ellis, Sylvia D. *Advanced Internet Searching Techniques for Librarians*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 21, 1997.

Hall-Ellis, Sylvia D. *Texas Library Connection Full-Text Searching*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 13, 1996 and October 25, 1996.

Hall-Ellis, Sylvia D. *Developing Evaluation Strategies for Grants and Proposals*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 10, 1996.

Hall-Ellis, Sylvia D. *Developing Needs Assessment for Grants and Proposals*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 12, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection Union Catalog Searching*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 8, 1996 and September 6, 1996.

Hall-Ellis, Sylvia D. *Grant Resources on the Internet*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 23, 1996.

Hall-Ellis, Sylvia D. *Preparing a Response to the Telecommunications Infrastructure Fund Board: Needs Assessment, Professional Development Framework, and Evaluation Strategies*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 16, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection: Building the Districtwide Bibliographic Database*. Sponsored and hosted by Mercedes Independent School District, Mercedes, Tex., September 13, 1996 and August 8, 1996. Sponsored and hosted by Los Fresnos Consolidated Independent School District, Los Fresnos, Tex., August 12, 1996.

Hall-Ellis, Sylvia D. *School-to-Work and Special Education: An Inclusive Partnership for Success*. Sponsored and hosted by the Office of Special Education, Region One Education Service Center, Edinburg, Tex., September 11, 1996.

Hall-Ellis, Sylvia D. *Telecommunications Infrastructure Fund Board: An Overview of Funding for Secondary Schools*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., August 31, 1996.

Hall-Ellis, Sylvia D. *Cataloging Books, Multimedia, and Realia in USMARC*. Sponsored and hosted by Edinburg Consolidated Independent School District, Edinburg, Tex., August 6, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers*. Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 20, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills for Mathematics Educators: Writing Skills for Campus Teams*. Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 22, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers*. Sponsored and hosted by the College of Education and Applied Science, Sam Houston State University, Huntsville, Tex., March 9, 1996.

Hall-Ellis, Sylvia D. *Grant Writing for Mathematics Educators: A Development Process for Campus Teams*. Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 4, 1996.

Hall-Ellis, Sylvia D. *Shaking the Money Tree: Preparing Successful Technology Grant Applications*. Sponsored and hosted by the Office of Technology and Media Services, Region One Education Service Center, Edinburg, Tex., February 29, 1996 and April 29, 1996.

Hall-Ellis, Sylvia D. *District-wide Technology Planning: Technical Assistance for the Texas Education Agency Initiative*. Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., February 2, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills*. Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 27, 1996.

Hall-Ellis, Sylvia D. *United States Copyright Act of 1976, Video Transmissions, Computer Software and the Internet*. Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., January 24, 1996.

Hall-Ellis, Sylvia D. *The Grant Writing Development Process*. Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 20, 1996.

Hall-Ellis, Sylvia D. *MARC Cataloging of Materials for Library Media Centers*. Sponsored and hosted by the Office of Media Services, Region One Education Service Center for the Donna Independent School District, Donna, Tex., August 17, 1995.

Hall-Ellis, Sylvia D. *Classification*. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 10, 1995.

Hall-Ellis, Sylvia D. *Library Technical Services*. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., April 26, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: An Introduction for Public School Administrators*. Sponsored and hosted by the Office of Administrative Services, Region One Education Service Center, Edinburg, Tex., April 19, 1995.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future*. Sponsored and hosted by the United Independent School District, Laredo, Tex., March 31, 1995.

Hall-Ellis, Sylvia D. *Using USMARC*. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 29, 1995.

Hall-Ellis, Sylvia D. *Library Media Center Policies and Guidelines: How to Prepare for School Board Adoption*. Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., March 10, 1995.

Hall-Ellis, Sylvia D. *Developing District-wide Policies and Guidelines for Library Media Centers*. Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., January 10, 1995.

Hall-Ellis, Sylvia D. *MARC Cataloging of Audiovisual Materials for Library Media Centers*. Sponsored and hosted by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., December 1, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future*. Sponsored and hosted by United Independent School District, Laredo, Tex., October 14, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future*. Sponsored and hosted by the Laredo Independent School District, Laredo, Tex., October 7, 1994.

Hall-Ellis, Sylvia D. *MARC Cataloging for Library Media Centers*. Sponsored by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., October 5, 1994.

Hall-Ellis, Sylvia D. *Jump to the Head of the Class: Undergraduate Library Resources Available at Sam Houston State University*. Sponsored by the Office of the Associate Vice President for Student Services, Sam Houston State University, Huntsville, Tex., October 4, 1994.

Hall-Ellis, Sylvia D. *CD-ROMs - 1994's Newest and the Best for Secondary Level Media Centers*. Sponsored and hosted by Clear Lake Independent School District, Houston, Tex., June 3, 1994.

Hall-Ellis, Sylvia D. *Introduction to Classification*. Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., May 18, 1994.

Hall-Ellis, Sylvia D. *Basic Descriptive Cataloging*. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part II: Writing Successful Grant Applications*. Sponsored by Donna Independent School District, Donna, Texas, and Region One Education Service Center Edinburg, Texas; presented at South Texas Community College Library, McAllen, Tex., April 29, 1994.

Hall-Ellis, Sylvia D. *Using MARC*. Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., April 6, 1994.

Hall-Ellis, Sylvia D. *Automated Authority Control*. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 23, 1994.

Hall-Ellis, Sylvia D. *Automating the District School Library Media Centers: Choices and Opportunities*. Sponsored and hosted by the Office of Technology and Library Media Services, Fort Bend Independent School District, Sugar Land, Tex., March 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part I: Preparing Successful Grant Applications*. Sponsored and hosted by the Office of Library Media Services, Donna Independent School District, Donna, Tex., February 4, 1994.

GRADUATE COURSES TAUGHT

San José State University, School of Library and Information Science

INFO 249 – Advanced Cataloging and Classification (Fall 2015, 2016; Summer 2016)
INFO 287 – Special Topics in Cataloging and Classification (Spring 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Fall 2020, 2021, 2022, 2023, 2024)
LIBR 248 – Beginning Cataloging and Classification (Summer 2002, 2003, 2004, 2005, 2006)
LIBR 249 – Advanced Cataloging and Classification (Summer 2003; Fall 2014; Summer 2015)

University of Denver, University College

Grant Writing Certificate Seminar for Non-Profit Organizations (Fall 2020, 2021; Spring 2021)

University of Denver, Morgridge College of Education HED

5991 – Grant Writing in Higher Education (Spring 2011)
LIS 4010 – Organization of Information (Fall 2002-2009; Winter 2005; Spring 2004-2006)
LIS 4020 – Professional Principles and Ethics (Summer 2000)
LIS 4040 – Management of Libraries and Information Centers (Fall 2010; Spring 2003, 2009 (DS); Winter 2005)
LIS 4070 – Cataloging and Classification (Winter 2008, 2009, 2010, 2011, 2012; Fall 2009 (DS)) LIS
4321 – Collection Management (Spring 2005)
LIS 4326 – LIS Research (Winter 2009 (DS); Spring 2009 (DS))
LIS 4350 – Adult Materials and Services (Summer 2006, 2009)
LIS 4379 – Social Sciences Resources (Spring 2009)
LIS 4400 – Cataloging and Classification (Spring 2000, 2001; Winter 2002-2009; Summer 2005, 2006 – course renumbered LIS 4070, September 2007)
LIS 4401 – Descriptive Cataloging (Winter 2001; Spring 2002, 2003, 2006-2009; Summer 2005)
LIS 4402 – Subject Cataloging (Spring 2001, 2009; Summer 2005, 2006, 2007, 2008)
LIS 4403 – Classification Schemes (Fall 2007, 2008, 2009 (DS)) LIS
LIS 4405 – Authority Control (Winter 2009)
LIS 4510 – Materials and Services for Children (Winter 2004; Summer 2005)
LIS 4620 – Grant Writing and Fundraising (Summer 2000, 2002, 2004, 2010; Winter 2006; Fall 2006-2009)
LIS 4700 – Seminar in Technical Services (Fall 2001)
LIS 4700 – Seminar in Public Libraries (Summer 2002)
LIS 4804 – Management of Electronic Records (Spring 2004; Fall 2005)
LIS 4902 – Capstone Projects (Winter 2003, Spring 2008, 2009, 2011)
LIS 4910 – Independent Study (every quarter Winter 2000 through Spring 2011)
LIS 4920 – Service Learning (every quarter Summer 2004 through Spring 2011)
RMS 4954 – Grant Writing (Summer 2013, 2014)
RMS 4959 – Content Analysis Methodology (Spring 2015)
QRM 4978 – Grant Writing (Summer 2011, 2012)

Rutgers University, School of Communication and Information

SC&I 522 – Cataloging and Classification (Summer 2013)

University of Arizona, College of Behavioral and Social Sciences

LIS 602 – Cataloging and Classification (Summer 1995)
LIS 612 – Advanced Online Search and Retrieval (Summer 1995)

Sam Houston State University, College of Education & Applied Science

LIS 532 - Cataloging and Classification (Fall 1993, 1994, 1995)
LIS 563 - Advanced Cataloging and Classification (Summer 1994)
LIS 567 - Research Methods (Spring 1994, Spring 1995)
LIS 591 - Educational Technology (Spring 1994, 1995)
LIS 596 - Networking and Computer Technologies in Education (Fall 1993, Summer 1994, Fall 1995)

Dissertations at the University of Denver

- Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale*. Chair, May 5, 2010.
- Fattor, Melissa M. *Student Engagement Differences by Ethnicity and Scale for Ninth Grade Students*. Chair, November 1, 2010.
- Fulton, Roseanne. *A Case Study of Culturally Responsive Teaching in Middle School Mathematics*. Kent Seidel, Chair, June 18, 2009, Outside Chair.
- Greal, Deborah S. *Tribes and Territories in Library and Information Studies Education*. Bruce Uhrmacher, Chair, June 10, 2008, Committee Member.
- McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice*. Chair, April 15, 2011.
- Priebe, Sarah J. *Distinguishing Effects of Domain and General Knowledge on Passage Fluency and Comprehension*. Jan Keenan, Chair. July 21, 2011, Outside Chair.
- Snyder-Mondragon, Sandra M. *Institutional Factors that Impact the Retention of Graduate Students of Color in Schools of Library and Information Science: A Metaregression of Accredited Library School Statistics on Student Retention and Graduation Rates*. Kathy Green, Chair, July 24, 2009, Committee Member.
- Taylor, Karen Pickles. *Effective Teaching*. Elinor Katz, Chair, July 15, 2009, Outside Chair.
- Thompson, Jennifer. *Distinguishing a Western Women's College: A History of the Curriculum and Student Experience at Colorado Women's College*. Edith W. King, Chair, July 16, 2010, Committee Member.
- Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions*. Chair, April 29, 2010.

Dissertation Proposals at the University of Denver

- Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale*. Chair, November 5, 2009.
- McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice*. Edith W. King, Chair. April 23, 2010.
- Thompson, Jennifer. *History of Colorado Women's College*. Edith W. King, Chair, October 30, 2008. Committee Member.
- Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions*. Chair, July 21, 2009.

Dissertations at Other Institutions

- Rodríguez-Mori, Howard. *The Information Behavior of Puerto Rican Immigrants to Central Florida, 2003-2009: Grounded Analysis of Six Case Studies Use of Social Networks during the Migration Process*. Kathleen Burnett, Chair, April 10, 2009, Florida State University, Committee Member.
- Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools*. D. Mirah Dow, Chair, July 18, 2017. Emporia State University, Committee Member.
- Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers*. Shawne D. Miksa, Chair, August 1, 2011. University of North Texas, Committee Member.

Dissertation Proposals at Other Institutions

Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools*. D. Mirah Dow, Chair, December 4, 2015. Emporia State University, Committee Member.

Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers*. Shawne D. Miksa, Chair, May 11, 2010. University of North Texas, Committee Member.

Master's Thesis at the University of Denver

Hemingson, Jeff. *Recital Paper*. Lamont School of Music, February 2010, Outside Chair.

Capstones at the University of Denver

Anthony, Alisa. *Correlation of Library and Information Science Program outcomes and Vacant Position Qualifications Listed on the Colorado State Library Jobline by Employers During the Period September 1, 2000 through August 31, 2002*. Chair, Winter Quarter, 2003.

Borden, Donna M. *Improving Emergency Communications Systems: Is a Radio Communications Network the Answer?* Fall Quarter, 2014.

Bowden, Heather L.M. *Exploring Biological Models for Long-term Data Preservation*. Chair, Spring Quarter, 2008.

Casenada, Cassandra Y. *Challenges to the Recruitment, Education, and Retention of Librarians of Color*. Chair, Spring Quarter, 2008.

Chang, Jennifer C. *Legal Research Practice and Preference: A Law Firm Perspective*. Chair, Spring Quarter 2011.

Ellis, Megan S. Fitzgerald. *Design of a Public Library Adult Volunteer Recruitment Program and Training Curriculum*. Chair, Winter Quarter, 2003.

Kircher, Kathy. *Development of a Library Pathfinder for Exobiology and Posting it on the Internet*. Chair, Winter Quarter, 2003.

Melhado, Loretta. *Design of St. John's Episcopal Church Library*. Chair, Spring Quarter, 2008.

Radcliff, Kathy. *Original Cataloging of Archival materials in the HERS Collection in Penrose Library*. Chair, Winter Quarter, 2003.

Sass, Carol Ann. *ACT Periodical Index: Access to Catholic Thinking Periodical Index: Web Index to Select Catholic Periodicals*. Spring Quarter 2000.

Stone, Sergio D. *Conducting Community Analysis for the Bemis Public Library (Littleton, Colorado) Using 2002 U.S. Census Data and the Online Outcome-Based Evaluation Toolkit*. Chair, Winter Quarter, 2003.

Tureson, Tamara. *Design and Use of an Information Audit Tool for Use in a Law Library*. Chair, Winter Quarter, 2003.

Tweed, Beth. *Evaluation of Email Reference Service in a Consumer Health Library Environment*. Chair, Winter Quarter, 2003.

GRANTS AND CONTRACTS

Student Learning in Agriculture STEM through Teacher Professional Development. Research team: Stanton Gartin (PI) and Cyndi Hofmeister, Northeast Junior College; Jeff Cash, Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Jack Wiley, Kerry Gabrielson, Trinidad State Junior College; Michael J. Miller, Colorado State University; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Agriculture and Food Research Initiative, Food, Agriculture, Natural Resources and Human Sciences Education and Literacy Initiative, \$404,460 (2017-2020)

Leading and Achieving: the Colorado Agriculture Regional Consortium. Research team: Jack Wiley (PI), Kerry Gabrielson, Trinidad State Junior College; Jeff Cash (PI), Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Cyndi Hofmeister, Northeast Junior College; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Hispanic Serving Institutions Education Grants Program, \$504,414 (2017-2020)

Cyber Prep Program Planning Grant. Research team: Debbie Sagen (PI), Brenda Lauer, Pikes Peak Community College; Gretchen Martin, Koiosa Insights; and, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Commerce, Regional Alliances and Multi-stakeholder Partnerships to Stimulate (RAMPS) Cybersecurity Education and Workforce Development, \$199,681 (2016-2018)

Career and Technical Education in Colorado: Pathways to Education and Employment. Research team: Heather McKay (PI), Rutgers University; Sarah Heath, Casey Sacks, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, Institute of Education Sciences, \$1,400,000 (2017-2021)

Pre-Alliance Planning Grant Colorado Community College Alliance. Research team: Victor Vialpondo (PI) and Janel Highfill, Community College of Aurora; Heidi Loshbaugh (Co-PI), Community College of Denver; Rick Reeves, Bill McGreevy, Liz Cox, and Kristin Aslin, Red Rocks Community College; Cathy Pellish, Front Range Community College; Samuel DeVries, Arapahoe Community College; Sylvia D. Hall-Ellis, Colorado Community College System. National Science Foundation, Louis Stokes Alliance for Minority Participation (LSAMP), \$86,817 (2016-2017)

Towards Scalable Differentiated Instruction Using Technology-enabled, Competency-based, Dynamic Scaffolding. Research team: Karen Wilcox (PI) and Vijay Kumar, Center for Computational Engineering, Massachusetts Institute of Technology; Flora McMartin, Broad-based Knowledge; Quinsigamond Community College; and, Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, First in the World Developmental Grant, \$2,891,882 (2015-2019)

Colorado Strategic Partnerships Emergency Grant. Research team: Elise Lowe-Vaughn (PI), Amy Hodson, Celia Hardin, Barbara McBride, James Newby, Christopher Dewhurst, Nina Holland, Kate Anderson, MaryAnn Roe, Chrystalynn Chrystalynn, Elaine Edon, Mona Barnes, Tom Morgan, Rob Hanni, and Marie Valenzuela, Colorado Department of Labor and Employment; Steve Anton, Joelle Brouner, and, Katie Griego, Colorado Department of Human Services; Rebecca Holmes, Judith Martinez, and Jennifer Jirous, Colorado Department of Education; Emily Templin Lesh, Colorado Workforce Development Council; Cory Everett, Colorado Department of Regulatory Agencies; and, Casey Sacks and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Labor, Strategic Partnerships Emergency Grant, \$5,000,000 (2015-2017)

CAEL Jump Start Program: Competency-Based Education. Research team: Jerry Migler (PI), Casey Sacks, Debra Cohn, Thomas Hartman, and Sylvia D. Hall-Ellis, Colorado Community College System; Matt Jamison, Front Range Community College; Mike Coste, Red Rocks Community College; Amanda Corum, Pueblo Community College; Janet Colvin, Pikes Peak Community College; and, MaryAnn Matheny, Community College of Denver. Council for Adult and Experiential Learning, \$15,000 (2015)

Summit on the Redesign of Developmental Education. Research team: Jerry Migler (PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System; Chip Nava, Pueblo Community College; Kim Moultny, Arapahoe Community College; Debbie Ulibarri, Trinidad State Junior College; and, Kris Bernard, Front Range Community College. American Association of Community Colleges, \$15,000 (2015-2016)

Equity in Excellence at Colorado Community Colleges. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Estela Mata Bensimon, Center for Urban Education, University of Southern California; and Kerry Gabrielson, Trinidad State Junior College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, \$150,000 (2015-2016)

MBA High School of Business in Colorado. Research team: Laurie Urich (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Rudolph Sumpter and Beatrice Gerrish, Boulder Valley Schools; Keith Curry Lance, RSL Research Group. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, \$501,295 (2015-2016)

Fullbridge Program in Colorado. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Suzanna Spears, Fort Morgan Community College; and, Cheryl Sánchez and Anne-Marie Compton, Lamar Community College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, \$300,000 (2015-2017)

Colorado Community College System Alternative Credit Program. Research team: Jerry Migler (PI), Keith Howard, and Sylvia D. Hall-Ellis, Colorado Community College System. American Council on Education, \$13,000 (2015)

Internationalization in Higher Education. Researcher: Samuel D. Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$8,000 (2014-2015)

International Perspectives on Bilingual Education. Researcher: Sharolyn Pollard-Durodola. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$3,700 (2014-2015)

Cultivating Culturally Relevant and Responsive Curriculum and Pedagogy in College. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, iRise Grant, \$5,000 (2014-2015)

Project EMERGE (Educational Model for Evaluation and Replicability in Gifted Environments). Research team: Norma Hafenstein (PI) and Bruce Uhrmacher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Lynde and Harry Bradley Foundation, \$235,000 (2014-2015)

Collecting Asian American Refugee Stories. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. American Educational Research Association, Research Grant, \$5,000 (2014-2015)

Developing Expertise in Teaching K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas H. Clements (Co-PI), in partnership with the School of Education at the University of Michigan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, \$130,344 (2013-2015)

Investigation of the Long-Term Outcomes for Special Education Students. Researcher: Antonio Olmos-Gallos. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Jefferson County School District, Office of Assessment, \$40,000 (2014)

Refugee Community Collaboration. Researcher: Vicki Tomlin (PI) in partnership with the African Community Center and Jewish Family Service. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, \$14,854 (2014-2015)

Access to Mathematics for All. Research team: Richard S. Kitchen (PI), Nicole M. Russell (Co-PI), and Terrence Blackman (Co-PI), Curriculum Studies and Teaching Program, Morgridge College of Education; Álvaro Árias (Co-PI, Department of Mathematics); and, James Gray (Co-PI), Department of Mathematics, Community College of Aurora. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, The Robert Noyce Scholarship Program, Capacity Building Project, \$349,926 (2014-2016)

Cognitive Test Battery for Intellectual Disabilities. Research team: Karen Riley (PI), Lyndsay Agans, Jessica Lerner, and Karin Dittrick-Nathan in partnership with David Hessel (PI), The MIND Institute at the University of California – Davis, and Elizabeth Berry-Kravis, Rush University Medical Center. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Institutes of Health, Outcome Measures for Use in Treatment Trials for Individuals with Intellectual and Developmental Disabilities (R01), \$2,499,996 (\$588,672 at DU) (2014- 2019)

Broadening Participation in Engineering among Women and Latino/as: A Longitudinal, Multi-Site Study. Researcher: Patton Garriott (PI) in partnership with the University of North Dakota and the University of Missouri. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, HER Core Research, \$677,390 (\$69,992 at DU) (2014-2019)

Designing a Teacher Evaluation System to Improve Teacher Effectiveness for Culturally and Linguistically Diverse Learners. Research team: María del Carmen Salazar (PI), Jessica Lerner, and Kathy Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, \$29,988 (2014-2016)

Developing a College-Going Culture in Latina/O Families: Exploring the Influence of Funds of Knowledge on Family Outreach Programs. Researcher: Judy Marquez Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, \$18,720 (2014-2016)

Assessment of Quality of Life in Neural Implantation Surgery for the Treatment of Parkinson's Disease. Researcher: Cynthia McRae. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$3,967 (2014-2015)

Pura Vida: Cloud Forest, Curriculum and Cross-Cultural Study. Research team: Norma Hafenstein (PI) and Bruce Uhrmacher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$8,000 (2014-2015)

Online Course Development for Curriculum and Instruction. Researcher: Ruth Chao. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: María del Carmen Salazar. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Jessica Lerner. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$3,000 (2014)

The Mathematics Education of African Americans, 1866 – 1954. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, \$55,000 (2014-2016)

Early Childhood Care and Education Study. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota, Department of Public Instruction, \$73,500 (2013-2014)

Graduate Level Specialty in Addiction Counselor Training with Emphasis on Integration of Native American Specific Content. Research team: Ruth Chao (PI) and Michael J. Faragher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Galena Foundation, \$289,732 (2013-2016)

The Collecting Asian American and Pacific Islander Refugee Stories (CARS) Project. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, \$15,000 (2014)

Parents in Transition: A Multiple Case Study of Parent and Family Orientation Programs. Researcher: Judy Marquéz Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, \$1,500 (2014-2015)

The Sistah Network: Black Women Graduate Students Supporting and Retaining Each Other. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, \$2,708 (2014-2015)

Evaluation of the Northeast Denver Babies Ready for College Program. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High Montessori, \$9,922 (2013-2014)

Developing Teaching Expertise in K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas Clements (University of Denver), in partnership with Timothy Boerst (PI), Meghan Shaughnessy, Deborah Ball, Hyman Bass (School of Education at the University of Michigan). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, \$449,827 (\$130,344 at the University of Denver) (2013-2015)

Early Learning Care and Education Study Program Grant for the State of North Dakota. Research team: Carrie Germeroth (PI), Melissa Mincic, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota Department of Public Instruction, \$73,500 (2013-2014)

Local Professional Learning Community for School Leaders. Research team: Susan Korach (PI), Kristina Hesbol, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Education Development Center, \$10,950 (2013)

Healthy Eaters, Lifelong Movers 2: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado. Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, \$3,103,108 (2013-2017)

Hughes Rare Books Library Room Renovation in the Sturm College of Law. Project team: Patti H. Marks, Sylvia D. Hall-Ellis, and Leigh Elliott. Mabel T. Hughes Charitable Trust, \$34,000 (2013-2014)

The Promise Center Partnership with the Marsico Institute for Early Learning and Literacy and the City and County of Denver. Research team: Karen Riley (PI), Douglas H. Clements (Co-PI), and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Piton Foundation, \$223,468 (2013-2014)

Center of Excellence for Problem Gambling. Research team: Ruth Chao (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, \$68,021 (2012-2013)

United Way Implementation and Validation Review. Research team: Douglas H. Clements (PI), Amanda Moreno, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, \$19,737 (2013)

Math/Science Partnership in Rural Districts. Research team: Kristen Bunn (PI, Eagle County Schools), Paul Michalec (Co-PI), and Alegra Reiber. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Colorado's Mathematics and Science Partnership Program, \$750,000 (2013-2014)

Mathematics and Science Education of African Americans. Research team: Nicole Russell (PI), Sylvia D. Hall-Ellis, Steve Fisher (Penrose Library). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, \$29,994 (2013-2015)

Online Course Development for Curriculum and Instruction. Researcher: Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$3,000 (2013)

Discourse and Opportunity: Undocumented Students and Higher Education Policy. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, \$55,000 (2012-2014)

An Anthropological Study of the Latino Graduation Ceremony. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Spencer Foundation, \$39,900 (2012-2013)

Fragile-X and Pharmaceutical Company: Clinical Trial of AFQ056. University of California – Davis Children's Hospital MIND Institute (Sacramento), Children's Hospital Denver, and Rush Children's Hospital at Rush University Medical Center (Chicago). Karen Riley, PI. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Novartis Pharmaceuticals Corporation, \$394,206 (2012-2014)

Project Engage, Phase 2, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University. Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, \$60,000 (2011-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, \$14,951 (2012-2013)

Online Course Development for Curriculum and Instruction. Research team: Bruce Uhrmacher (PI) and Norma Hafenstein (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, \$18,193 (2012-2014)

Writers in the Schools. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Humanities, \$4,965 (2012-2013)

Learning Ecosystem Validation Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, \$315,000 (2012-2013)

Project Words of Oral Reading and Language Development (WORLD). Research team: Jorge E. Gonzalez (PI), Texas A&M University; Laura Saenz (Co-PI), University of Texas – Pan American; and, Sharolyn Pollard-Durodola (Co-PI), University of Denver. Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, \$53,354 (2012-2015); award \$640,718, transfer from Texas A&M University

Increasing the Efficacy of an Early Mathematics Curriculum with Scaffolding Designed to Promote Self-Regulation. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, \$1,445,315 (2008-2014); award \$4,541,975, transfer from University at Buffalo, The State University of New York

Using Rule Space and Poset-based Adaptive Testing Methodologies to Identify Ability Patterns in Early Mathematics and Create a Comprehensive Mathematics Ability Test. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, \$323,791 (2010-2014); award \$1,194,944, transfer from University at Buffalo, The State University of New York

Comprehensive Postdoctoral Training in Scientific Education Research. Researcher: Julie Sarama (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, \$133,458 (2010-2014); award \$613,353, transfer from University at Buffalo, The State University of New York

Longitudinal Study of a Successful Scaling Up Project: Extending TRIAD. Research team: Douglas H. Clements (PI), Julie Sarama (Co-PI), and Abt Associates (Carolyn Layzer, Fatih Unlu, Laurie Bozzi, Lily Fesler, Alina Martinez, Cristofer Price, James van Orden). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, \$384,940 (2011-2015); award \$1,250,286, transfer from University at Buffalo, The State University of New York

Early Childhood Education in the Context of Mathematics, Science, and Literacy. Research team: Julie Sarama (PI), Douglas H. Clements (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, \$990,020 (2010-2014); award \$2,285,228, transfer from University at Buffalo, The State University of New York

Early Childhood Clearinghouse Information Center Redesign. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Office of the Lt. Governor of Colorado, \$12,000 (2012-2013)

Morgridge Rural Educational Leadership Initiative. Research team: Lyndsay Agans (PI), Linda Brookhart (Co-PI), Susan Korach, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, \$100,000 (2012-2014)

Center of Excellence for Problem Gambling. Research team: Patrick Sherry (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, \$55,000 (2012-2013)

Intermodal Transportation Institute Research Initiatives. Researcher: Patrick Sherry. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University Transportation Centers Program, Research and Innovative Technology Administration, U.S. Department of Transportation. \$600,000 (2012-2014)

Mile High United Way Social Innovation Fund Early Literacy Initiative. Gloria L. Miller, PI, Amanda Moreano, Kim Hartnett-Edwards, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, \$89,992 (2012-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, \$1,000 (2012-2013)

Refugee Student Art Outreach. Researcher: Karin Ditttrick-Nathan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, \$3,000 (2012-2013)

Resistance, Resilience, and Reciprocity: Centering the Voices of Black Doctoral Women with Faculty Aspirations. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, \$2,965 (2012-2013)

Assessing Learning through Student Notebooks. Research team: Keith Miller, Nancy Sasaki, and Kathy Green.

Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, \$30,000 (2012-2014)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$2,000 (2012-2013)

ELO in Colorado. Research team: Cynthia Hazel and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Legacy Foundation, \$150,000 (2012-2013)

Creating Online LIS Courses. Research team: Mary C. Stansbury (PI), Shimelis Assefa, Denise Anthony, Xiao Hu, and Krystyna Matusiak. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, \$15,000 (2011-2013)

Maritime Piracy Seminar. Researcher: Ved Nanda, The Nanda Center, Sturm College of Law. Technical reviewer for Sturm College of Law: Sylvia D. Hall-Ellis. Arsenault Family Foundation, \$15,000 (2012-2013).

Early Childhood Librarianship: An Interdisciplinary, Experiential Learning MLIS. Researcher: Mary C. Stansbury (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, \$249,066 (2012-2014)

Learning Ecosystem Planning Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, \$281,217 (2011-2012)

Advanced Service Learning Practitioner Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, \$400 (2011)

Evaluating and Enhancing the EspeciallyMe Program. Research team: Lori D. Patton and Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Fellowship Grant, \$24,780 (2012)

Choosing Excellence: Let Every Child Bloom. Research team: Shimelis Assefa (PI) and Mary C. Stansbury (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Grant, \$7,657 (2012)

K-8 STEM Content Specific Professional Development to Improve Elementary Student Achievement. Research team: Kent Seidel (PI), Nicole Russell (Co-PI), Kimberly Hartnett-Edwards, Paul Michalec, Jeff Farmer, Keith Miller, Alegra Reiber, and Nancy Sasaki. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Improving Teacher Quality Grant, (Title II ESEA), \$307,299 (2011-2012)

Building a Better Principal Pipeline to Boost Student Achievement. Researcher: Susan Korach. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools; a subcontract from the Wallace Foundation Grant, \$170,000 (2011-2017)

Center of Excellence for Problem Gambling. Research team: J. Mike Faragher (Co-PI) and Bobbie Vollmer (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, \$79,999 (2011-2012)

An Exploration of Novice Teachers' Core Competencies: Impacts on Student Achievement, and Effectiveness of Preparation. Research team: Kent Seidel (PI), Kathy Green (Co-PI), Kimberly Hartnett-Edwards, and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, Effective Teachers and Effective Teaching, \$990,987 (2012-2015)

Project Engage, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University.

Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, \$49,964 (2011-2014)

User-centered Evaluation of Music Search Engines. Researcher: Xiao Hu. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, \$2,931 (2011-2012)

Educational Practicum in Vietnam and China to Promote the Inclusion of Young Children with Disabilities.

Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, \$5,000 (2011-2012)

Evaluation of Colorado's Enhancing Quality in Infant-Toddler (EQIT) Initiative. Research team: Virginia R.

Maloney and Amanda Moreno. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Buell Foundation, \$395,884 (2011-2013)

Creating Engaging Environments to Teach Pre-Algebra Mathematics to Elementary Students. Research team:

Álvaro Arias, Mario López, María del Carmen Salazar, and Lyndsay Agans. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver Interdisciplinary Grant, \$60,000 (2011-2012)

Morgridge Education Technology Accessible (META) Resource Project. Research team: Lyndsay Agans (PI) and

Shimelis Assefa (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, \$36,000 (2011)

MCE Connect: A 21st Century Framework for Faculty Development. Research team: Bruce Uhrmacher (PI),

Shimelis Assefa (Co-PI), Lyndsay Agans (Co-PI), Kimberly Hartnett-Edwards, Norma Hafenstein, Xiao Hu, Paul Michalec (Co-PI), María del Carmen Salazar (Co-PI), and Sandra Snyder-Mondragon. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, \$22,355 (2011-2012)

Parent Education and Parent Leadership and Advocacy. Research team: Virginia Maloney (PI) and Amanda

Moreno, Marsico Institute for Early Learning and Literacy. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, \$27,358 (2010-2011)

Intentional School Culture. Researcher: Cynthia Hazel. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools, \$38,040 (2010-2011)

Healthy Eaters, Lifelong Movers: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado.

Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, \$1,683,277 (2011-2014)

Second Life Learning Community. Research team: Don McCubbrey (PI), Sylvia D. Hall-Ellis (Co-PI), Walter

LaMendola, and Paul Novak. University of Denver, Center for Teaching and Learning, \$13,000 (2010-2011)

Reintroducing the Value of Law Librarians to Academic and Public Librarians in Colorado through the

Identification and Use of Emerging Technologies. Research team: Sylvia D. Hall-Ellis (Co-PI), Stacey L. Bowers (PI), and Christopher Hudson, in partnership with Denver Public Library, Arapahoe Library District, and the Colorado State Supreme Court Library. University of Denver, Center for Community Engagement and Service Learning, \$5,773 (2010-11)

Reintroducing the Value of Law Librarians to Public Librarians through the Identification and Use of Emerging

Technologies and Resources. Research team: Stacey Bowers (PI) and Sylvia D. Hall-Ellis (Co-PI). American Association of Libraries, Wolters Kluwer Law & Business Grant Program, \$2,725 (2010-2011)

Faculty Service Learning Pod. Research team: María del Carmen Salazar and Nicholas Cutforth (Curriculum and Instruction Program), Frank Tuitt (Higher Education Program), Cynthia Hazel and Gloria Miller (Child, Family, and School Psychology Program), and Sylvia D. Hall-Ellis (Library and Information Science Program). University of Denver, Center for Community Engagement and Service Learning, \$8,000 (2010-2011)

Lincoln Collaborative. Research team: Antonio Esquibel (Principal, Lincoln High School), María del Carmen Salazar (Curriculum and Instruction Program), and Sylvia D. Hall-Ellis. School Improvement Grant, Denver Public Schools, \$375,000 (2010-2012)

Future LEADers of America: Leaders III. Research team: Denver Public Library (Kristen Svendsen, PI), the University of Denver (Sylvia D. Hall-Ellis), the Colorado Chapter of REFORMA (Orlando Archibeque), and the Colorado Association of Libraries (Martin Garnar). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, \$988,366 (2009-2012)

Teaching for Success in the Library Environment: LIS 4030 in Library 2.0. Research team: Deborah S. Greal (PI) and Sylvia D. Hall-Ellis (Co-PI). University of Denver, Center for Teaching and Learning, \$ 9,350 (2009-10)

Writing Group Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, \$750 (2008-2009)

Collaborative Learning Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Teaching and Learning, \$1,500 (2008)

Connecting Information Literacy to Learning. Research team: Lori Micho, Merrie Valliant, Amanda Samland, and Sylvia D. Hall-Ellis. Colorado State Library, LSTA Discretionary Grant Program, \$19,548 (2008-2009)

Law Librarianship Fellows Program. Research team: Sylvia D. Hall-Ellis (PI), Stacey Bowers (Co-PI), and Christopher Hudson, Westminster Law Library. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, \$999,370 (2008-2012)

Grant Writing in a Cooperative Learning Environment. Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, \$2,000 (2008-2009)

Project Homeless Connect 6 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, \$9,785 (2008)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, \$600 (2007)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, International Service Learning Office, University of Denver, \$400 (2007)

Project Homeless Connect 5 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, \$1,000 (2007)

Project Homeless Connect 4 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, \$4,595 (2007)

Future LEADers of America: Leaders II. Research team: Denver Public Library (Kristen Svendsen, PI), the University of Denver (Sylvia D. Hall-Ellis), and the Colorado Chapter of REFORMA (Orlando Archibeque). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, \$988,518 (2007-2010)

Strategic Planning Assistance for the Denver Medical Library. Sylvia D. Hall-Ellis. Denver Medical Library, Inc., \$30,000 (2006-2007)

Destiny Software for JMAC Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, \$10,000 (2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in France. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, \$800 (2005)

Denver Public Library: Opportunities for Change. Sylvia D. Hall-Ellis, Colorado Community Based Research Network, \$2,000 (2005)

Future LEADers of America. Research team: Denver Public Library (Letty Icolari and Steve Taylor, PIs), Emporia State University (Jim Agee), and the University of Denver (Sylvia D. Hall-Ellis). Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, \$670,315 (2005-2008)

American Association of University Professors Summer Institute Professional Development Grant. Sylvia D. Hall-Ellis, American Association of University Professors, \$300 (2005)

Beta Phi Mu Alumni Tea. Sylvia D. Hall-Ellis, gift from the Office of Alumni and Parent and Relations, University of Denver, \$2,000 (2005)

Spectrum Software for LIS Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, \$5,000 (2005)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Nicholas J. Cutforth (PI) and Sylvia D. Hall-Ellis. Piton Foundation, \$25,000 (2005-2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in Argentina. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, \$500 (2004)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Research team: Nicholas J. Cutforth (PI), Gary Lichtenstein and Sylvia D. Hall-Ellis, Piton Foundation, \$25,000 (2003-2004)

Increasing Spanish-Speaking and Hispanic Diversity among Library and Information Science Students at the University of Denver: Development of a Student Recruitment Model. Researcher: Sylvia D. Hall-Ellis (PI), Office of Multicultural Excellence, University of Denver, \$2,750 (2003-2004)

Collection Development Enrichment to Support the Cataloging & Classification Specialization and School Librarianship within the Library & Information Science Program at the University of Denver. Research team: Sylvia D. Hall-Ellis (PI) and Deborah S. Grealy. Women's Library Association, University of Denver, \$4,000 (2003)

Collection Development Enrichment to Support the Library & Information Science Program at the University of Denver. Research team: Deborah S. Grealy (PI) and Sylvia D. Hall-Ellis. Women's Library Association, University of Denver, \$4,000 (2001)

Wireless LAN for Library Education. Research team: Deborah S. Grealy (PI) and Sylvia Hall-Ellis. University of Denver, Center for Teaching and Learning, \$24,000 (2001-2002)

Upward Bound – A Program for South Texas Youth. Research team: Monte Churchill, Executive Director of Community Relations; Gary R. Saucedo, Outreach Coordinator; Raymond Hernandez, (PI) Associate Dean for Student Success; and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). U.S. Department of Education, Office of Postsecondary Education, \$2,672,003 (1999-2003)

Write Now! Improving Elementary Students' Writing Skills. Research team: Caryl G. Thomason, Assistant Superintendent (PI); Karen Tankersley, Principal; and, Hal Anderson, Director of Technology, Cheyenne Mountain School District 12 (Colorado Springs, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, \$189,453 (1999-2001)

Operation Quick Start -- Distance Learning in Rural Colorado. Research team: Randal Weigum, Technology Coordinator (PI); Bonnie Barns, Director of Federal Programs and Staff Development; and, Adam "Joe" Raskop, Executive Director, Southeastern Board of Cooperative Educational Services (Lamar, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, \$400,000 (1999-2001)

Advanced Technological Training for Information Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Phi Delta Kappa and the National Science Foundation, \$250,000 (1999-2001)

Working Connections – Training Information Technologies Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Microsoft Corporation and the American Association of Community Colleges, \$1,147,775 (1999-2001)

The ROAD (Research Oriented Amplification of Development to Literacy) Program. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Foundation, \$25,000 (1998-1999)

Press to Literacy. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). The Denver Post and the Robert S. McCormick Foundation, \$49,818 (1998-1999)

International Telementor Center. Research team: David Neils, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Philanthropy, \$100,000 (1998-1999)

America Reads: Providing Tutor Training for the America Reads Challenge. Research team: Louis F. Cicchinelli (PI) and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, \$306,000 (1998-1999)

Comprehensive School Reform. Research team: Louis F. Cicchinelli (PI), J. Timothy Waters, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, \$285,000 (1998-1999)

Sustainable Energy Education (SEE) Program for Grades 4-8: Preparing Today's Youth for Lifelong Learning and Responsible Actions in Energy Conservation. Research team: Mary Gromko, Colorado Department of Education; Gene McCarthy, Rocky Flats Field Office, U.S. Department of Energy; Gina Kissell, National Renewable Energy Laboratory; and Barbara L. McCombs (PI), Janet L. Bishop, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). State of Colorado Governor's Office for Energy Conservation, \$499,936 (1997-1999)

Review of Kansas Curriculum Standards in Mathematics and Language Arts. Research team: Robert J. Marzano (PI), John S. Kendall, David B. Frost, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Submitted to the Kansas State Department of Education, \$25,903 (1998)

International Telementor Center. Research team: David Neils, John Kuglin, Chris Rapp, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Company, \$54,752 (1998)

Genesis Mission: Education Public Outreach. Developed in partnership by the Jet Propulsion Laboratory, California Institute of Technology, Los Alamos National Laboratory, Lockheed Martin Astronautics, and the Mid-continent Regional Educational Laboratory (Aurora, Colorado). Research team: John T. Sutton (PI), Alice Krueger, Martha Henry, Greg Rawls, Shae Isaacs, Jeff Johnson, Deb Jordan, Arlene Mitchell, David B. Frost, Jana Caldwell, J. Timothy Waters, and Sylvia D. Hall-Ellis. National Aeronautics and Space Administration, \$139,700,000; subcontract award, \$4,750,000 (1997-2007)

North Dakota Mathematics Assessment Project. Developed in partnership by the North Dakota Department of Education and Mid-continent Regional Educational Laboratory (Mid-continent Regional Educational Laboratory). Research team: Ann Clapper, Clarence Bina, Greg Gallagher, North Dakota Department of Education; Don Burger (PI), Hillary Michaels, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, \$1,618,214; subcontract award, \$389,076 (1997-2001)

Pacific Resources for Education and Learning Distance Education: Project Evaluation. Developed in partnership by the Pacific Educational Community, the Pacific Resources for Education and Learning (PREL), and Mid-continent Regional Educational Laboratory (McREL). Research team: John W. Kofel (PI), Executive Director, PREL; J. Timothy Waters, Executive Director; Joan Buttram, Robert Keller, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, Star Schools Program, \$10,000,000; subcontract award, \$500,000 (1997-2002)

Identification of Bilingual Gifted and Talented Children: A Comprehensive School Grants for Bilingual Education. Developed in partnership by Hidalgo (Texas) ISD, Los Fresnos (Texas) CISD, Progreso (Texas) ISD, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Hilda Medrano, Dean, College of Education, University of Texas – Pan American; Linda Phemister (PI), Janie Navarro, and Sylvia D. Hall-Ellis, Education Service Center, Region One. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, \$1,670,633 (1997-2002)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Jim Hogg (Hebbronville, Texas) County ISD, Mirando City (Texas) ISD, and San Isidro (Texas) ISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg, Texas); Angie Lehmann, Amy Mares, Ellen Gonzalez (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg, Texas). Texas Education Agency, \$339,987 (1997-2000)

Southwestern Bell's Learning Communities Initiative. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen, Texas); the Center for Professional Teacher Development, University of Texas – Brownsville; Teach for America – Rio Grande Valley (McAllen, Texas); and Education Service Center, Region One (Edinburg, Texas). Research team: Patricia G. Bubb, Executive Director (PI), Tech Prep of the Rio Grande Valley; Martin Winchester, Executive Director, Teach for America – Rio Grande Valley; Aileen Johnson, Director, School of Education, University of Texas – Brownsville; and Sylvia D. Hall-Ellis. Southwestern Bell Foundation, \$100,000 (1997-1998)

Texas School to Work: Regional Implementation. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), Texas State Technical College (Harlingen), Texas Southmost College (Brownsville), Empowerment Zone of the Rio Grande Valley (Mercedes), Project VIDA (Weslaco), Youth Fair Chance (McAllen), and Education Service Center, Region One (Edinburg). Research team: Patricia G. Bubb (PI), Tech Prep of the Rio Grande Valley; Stephen Vassberg, Texas State Technical College; Ellen Trevino, Youth Fair Chance; Wanda Garza, Project VIDA; Leonardo Olivares, University of Texas – Pan American; Michael Bell, South Texas Community College; and Sylvia D. Hall-Ellis. Texas Workforce Commission, \$4,250,000 (1997-2002).

Comprehensive Bilingual Education Grant for Hidalgo ISD and Roma ISD. Developed for Hidalgo (Texas) ISD, Roma (Texas) ISD, College of Education, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Tomas Thomas (PI), Director, Office of Bilingual Education and Sylvia D. Hall-Ellis. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, \$1,531,361 (1997-2002)

Lopez High School, Porter High School, Rivera High School, Central Middle School, and Perkins Middle School, Brownsville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$1,473,611 (1997-1998)

Donna High School, Todd Middle School, and Solis Middle School, Donna (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$704,052 (1997-1998)

Memorial Middle School and Nellie Schunior Middle School, La Joya Independent School District (Texas). Telecommunications Infrastructure Fund Board, \$293,641 (1997-1998)

Martin High School, Christen Middle School, Cigarroa Middle School, Lamar Middle School, Laredo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$1,200,000 (1997-1998).

Lasara Middle School, Lasara (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$246,210 (1997-1998)

Los Fresnos High School and Resaca Middle School, Los Fresnos (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, \$500,000 (1997-1998)

Lyford Junior High School, Lyford (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$354,997 (1997-1998)

Travis Middle School, McAllen (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$269,139 (1997-1998)

Mission High School, Mission (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$297,010 (1997-1998)

Progreso High School, Progreso (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$300,000 (1997-1998)

San Perlita High School, San Perlita (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$293,490 (1997-1998)

Myra Green Junior High School, Raymondville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$225,000 (1997-1998)

Rio Grande City High School, Ringgold Middle School, Gruella Middle School, Rio Grande City (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$809,934 (1997-1998)

Rio Hondo Junior High School, Rio Hondo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$297,024 (1997-1998)

Roma High School, Roma (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$333,178 (1997-1998)

San Benito High School, Miller Jordan Junior High School, San Benito (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, \$547,000 (1997-1998)

Santa Maria High School and Santa Maria Middle School, Santa Maria (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$400,000 (1997-1998)

Salvador High School, United Independent School District (Laredo, Texas). Telecommunications Infrastructure Fund Board, \$250,879 (1997-1998)

Weslaco High School, Cabaza Middle School, Cuellar Middle School, Weslaco (Texas) Independent School District. Telecommunications Infrastructure Fund Board, \$874,242 (1997-1998)

Principals' Assessment and Training Center. Developed for Education Service Center, Region One (Edinburg, Texas). Research team: Roberto Zamora, Leonel Barrera, William H. Parry, and Sylvia D. Hall-Ellis. Texas Principals' Leadership Initiative, Texas Association of Secondary School Principals, Texas Association of Elementary School Principals, and the Sid Richardson Foundation. \$461,439 (1996-1998)

The Texas Library Connection -- Integrating and Sharing Resources. Developed for Hidalgo County Library System (McAllen), Cameron County Library System (Brownsville), South Texas Community College (McAllen), the University of Texas - Pan American (Edinburg), University of Texas - Brownsville, and Education Service Center, Region One (Edinburg). Research team: William R. McGee, Coordinator, Hidalgo County Library System; Joe Garcia, Director, Cameron County Library System; Michael D. Bell, Library Director, South Texas Community College; Eleanor Folger Foster, University Library, University of Texas - Pan American; Jaime Vela (PI), Director of Instructional Technology and Media Services, Ron Pontius, Instructional Technology, and Fabiola Fuentes, Media Services, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Office of Library Media Services, Technology Services, Texas Education Agency. \$8,000 (1996-1997)

Developing Leadership Communities for Improving Algebra I for All Students. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Noel Villarreal (PI), Eduardo Cancino, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin. \$25,000 (1996-1997)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Edinburg (Texas) CISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg); Helen Jones, Director (PI), Gifted and Talented Education, Edinburg CISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, \$750,000 (1996-2001)

Texas Teachers Empowered for Achievement in Mathematics (TEXTEAM) Institute for Algebra I. Developed for Hidalgo ISD, Jim Hogg (Hebbronville) County ISD, La Joya ISD, La Villa ISD, Lyford ISD, Mission CISD, Pharr-San Juan-Alamo ISD, Rio Hondo ISD, San Isidro ISD, San Perlita ISD, Santa Maria ISD, Santa Rosa, Sharyland ISD, Valley View ISD, Webb (Laredo) CISD, Weslaco ISD, and Zapata County (Zapata) ISD. Research team: Noel Villarreal (PI), Chuck McInteer, Ellen M. Gonzalez, Education Service Center, Region One (Edinburg); and Sylvia D. Hall-Ellis. Charles A. Dana Center for Mathematics and Science Education, University of Texas - Austin, \$15,975 (1996)

Community Learning Center for La Villa, Texas. Developed for Edcouch-Elsa Independent School District. Research team: Noe Gonzalez (PI), Assistant Superintendent, Edcouch-Elsa Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, \$325,000 (1996-1997)

Monte Alto (Texas) Community Learning Center. Developed for Monte Alto Independent School District. Research team: Homero A. Diaz (PI), Superintendent, Monte Alto Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, \$300,000 (1996-1997)

Community Learning Center for La Villa, Texas. Developed for La Villa Independent School District. Research team: Sam Gonzalez (PI), Assistant Superintendent, La Villa Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, \$325,000 (1996-1997)

Building Project for Taylor Elementary. Developed for Mercedes (Texas) Independent School District. Research team: Mrs. Denise Rivera, Librarian, and Eduardo Infante, Principal, Taylor Elementary School; Ismael S. Cantu (PI), Federal Programs Director, Mercedes Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, \$375,000 (1996-1997)

Border Education Network (BEN) - Distance Education through Cable Television. Developed for Edinburg (Texas) Consolidated Independent School District. Research team: Noe Torres (PI), Library Media Specialist, Magdalena Rosas, Library Media and Technology Coordinator, Edinburg Consolidated Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Edinburg (Texas) Consolidated School District, \$250,000 (1996-1997)

Multiservice One-Stop Open Enrollment Charter School. Developed for the Information Referral Resource Assistance, Inc. (McAllen, Texas). Research team: Pablo Perez and Aguié Pena (PI), Executive Director, Information Referral Resource Assistance, Inc.; Roberto Zamora and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, \$3,066,000 (1996-2001)

Project OK: A Community Youth Opportunities Grant for Summer, 1996. Developed for McAllen (Texas) Independent School District, St. Joseph the Worker Catholic Church, and the Office of Adult Education, Education Service Center, Region One. Research team: Father Bart Flatt, St. Joseph the Worker Catholic Church; Noe Calvillo (PI), Office of Adult Education; Maria Louisa Garcia, McAllen Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Protective and Regulatory Agency through the Office of the Mayor, City of McAllen, \$350,000 (1996-2001).

Early Childhood: a Time of Discovery. Developed for a partnership of Lasara ISD, Rio Hondo ISD, San Perlita ISD, the School of Education, University of Texas - Brownsville, and Education Service Center, Region One (Edinburg). Research team: Hugo Rodriguez, Dean, School of Education, University of Texas - Pan American; Leonel Barrera and Jack Damron, Field Service Agents, Ellen M. Gonzalez (PI), Administrator for Student Instructional Services, Ruth Solis, Education Specialist in Special Education, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, \$722,090 (1996-2001)

Innovative Gifted and Talented Programs for Early Childhood and Elementary Education Students. Developed for a partnership of Edinburg (Texas) CISD, the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean,

School of Education, University of Texas - Pan American; Helen de la Garza (PI), Director of Elementary Curriculum and Instruction, Edinburg CISD; and Sylvia D. Hall-Ellis. Texas Education Agency, \$750,000 (1996-2001)

Reading Recovery in Early Elementary Grades. Developed for a partnership of La Villa (Texas) ISD the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean, School of Education, University of Texas - Pan American; Marcario Salinas (PI), Supervisor of Elementary Curriculum and Instruction, La Villa ISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One. Texas Education Agency, \$750,000 (1996-2001)

Connected Mathematics Project for Middle and Junior High Students. Developed for a partnership of Michigan State University, The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin and Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). National Science Foundation through Michigan State University to the Charles A. Dana Center at the University of Texas - Austin, \$539,610 (1996-1999)

Sharing Resources: Testing the Interlibrary Loan Potential of the Texas Library Connection -- Integrating Media Resources. Developed under the sponsorship of the Hidalgo County Library System (McAllen) and Education Service Center, Region One (Edinburg). Research team: William H. McGee, Hidalgo County System Coordinator; Fabiola Fuentes, Library Media; Ronald Pontius (PI), Instructional Technology, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Library Media Services Program, Office of Technology Services, Texas Education Agency, \$25,000 (1996-1997)

State and Federal Adult Education JOBS Program. Developed for Education Service Center, Region One (Edinburg). Research team: Noe Calvillo (PI), Director, Adult Education Program, and Sylvia D. Hall-Ellis. Adult Education Program, Texas Education Agency, \$532,846 (1995-1996)

Creating Safe and Drug-Free Schools and Communities. Developed for a partnership of the Region One Consortium for Safe and Drug-Free Education Environments. Research team: Clara Contreras (PI), Health Specialist, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, \$150,000 (1995-1996)

Developing Leadership Communities for Improving Mathematics Performance for All Students on Title I Campuses. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin, \$50,669 (1995-1996)

The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in South Texas. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville). Texas Association of School Librarians, Children's Services Round Table, and Young Adults Round Table (Austin, Texas), \$2,500 (1995)

School Library Media Specialists Fellowship Program. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville, Texas). U.S. Department of Education, HEA Title II-B, Library Education and Human Resource Development Program, \$44,000 (1995-1996)

Planning for Educational Technology. Research team: Ruth Ann Riggins (PI), Director of Library Media and Technology Services, Donna (Texas) Independent School District; Noe Torres, Education Service Center,

Region One; Patricia G. Bubb, Tech Prep of the Rio Grande Calley, Inc; Michael D. Bell, South Texas Community College; and Sylvia D. Hall-Ellis, Sam Houston State University. Developed under the sponsorship of Donna (Texas) Independent School District, Education Service Center, Region One (Edinburg), Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), and the Department of Library Science, Sam Houston State University (Huntsville). Funded through Infusion of Educational Technology Planning Grant Program (H.B. 18: Models). Texas Education Agency, \$18,000 (1993-1994)

The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in South Texas.

Sylvia D. Hall-Ellis (PI) and Mary Ann Berry. Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville). Sam Houston State University Research Enhancement Fund, \$7,500 (1993-1994)

Electronic Mail Resource Sharing System: Management and Operation of the Iowa Computer-Assisted Network. State Library of Iowa, \$294,000 (1986-1993)

The Iowa Locator: A CD-ROM Resource Sharing Tool. State Library of Iowa, \$567,000 (1986-1992)

Statewide Database Development: An OCLC Tape Analysis To Determine Feasibility. State Library of South Dakota, \$15,000 (1987)

The Iowa Locator: A Feasibility Study. State Library of Iowa, \$50,000 (1986)

Electronic Mail Resource Sharing System: A Feasibility Study for Libraries in the State of Iowa. State Library of Iowa, \$5,000 (1985)

Access Pennsylvania: A Feasibility Study. State Library of Pennsylvania, \$50,000 (1984)

Automating Library Administrative and Management Tasks: Procurement and Distribution of Microcomputer Systems for District Library Centers in the Commonwealth of Pennsylvania. State Library of Pennsylvania, \$495,000 (1982)

Sharing Serial Titles Resources: Procurement and Distribution of Microfiche Readers for 550 Libraries in the Commonwealth of Pennsylvania. State Library of Pennsylvania, \$500,000 (1982)

Electronic Mail System: A Pilot Project for Libraries throughout the Commonwealth of Pennsylvania. State Library of Pennsylvania, \$125,000 (1982)

Literacy Program for Adults in Rural Upstate New York State: Program Outreach and Evaluation - Phase 3. Appalachian Regional Commission, \$50,000 (1981)

Database Building: A Cooperative Project of the Finger Lakes Library System (Ithaca), Four County Library System (Binghamton), and the Southern Tier Library System (Corning). New York State Library, \$450,000 (1980-1985)

Faces of the Southern Tier: A Professional Photographer-in-Residence. New York State National Endowment for the Humanities, \$25,000 (1980)

Literacy Program for Adults in Rural Upstate New York State: Program Implementation - Phase 2. Appalachian Regional Commission, \$50,000 (1980)

Small Business Resources Center: A Pilot Project for Rural Public Libraries. New York State Library, \$50,000 (1980)

Media Programming: A Professional Development Program for Public Librarians in Upstate New York: A Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, \$35,000 (1979)

Information and Library Resources for Inmates and Prisoners in Selected Upstate New York Facilities: A Cooperative Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, \$25,000 (1979)

Library Resources for Homebound Adults in Upstate New York: An Outreach Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, \$40,000 (1979)

Literacy Program for Adults in Rural Upstate New York State: Program Initiation and Establishment - Phase 1. Funded by the Appalachian Regional Commission. Awarded to the Corning (New York) Public Library, \$50,000 (1979)

Information Reference Services to Homebound Adults. New York State Library, \$31,000 (1978)

Books-By-Mail Services to Homebound Adults. New York State Library, \$31,000 (1978)

System Headquarters Services and Programs for Public Libraries in District 10. Funded through Library Services and Construction Act Title I. Texas State Library and Historical Commission, \$880,000 (1976)

County Library Development Grant for Atascosita County. Funded through Library Services and Construction Act Title I. Texas State Library and Historical Commission, \$15,000 (1976)

Spanish Language Materials Collection Development Program. Texas State Library and Historical Commission, \$40,000 (1975)

Establishment of System Headquarters for Alamo Regional Library System (District 10) Headquartered at the San Antonio (Texas) Public Library. Texas State Library and Historical Commission, \$800,000 (1975)

SELECTED CONSULTANTSHIPS

Project Strategic Planning & Funding Proposal Development

Walden University, 2015.
Pikes Peak Library District, 2014.
Douglas County Public Libraries, 2011-2012.
Denver School for Science and Technology, 2008-2011.
Johnson & Wales University, Denver Campus, 2007-2009.
Challenges, Choices, and Images K-12 Charter School, Denver Public Schools, 2007.
Denver Medical Library, Inc., 2006-2010.
Bemis Public Library (Littleton), Ergonomic Design and Facilities Enhancement Consultant, 2003.
Curtis Park Community Center (Denver), Community Technology Center Evaluation and Proposal Development Consultant, 2003.
Colorado Community Based Research Network (Denver), Funding Research Associate, 2002.
Our Lady of the Rosary Academy (Edgewater), Learning Resource Center Development Project Consultant, 2001-2003
University of Southern Colorado (Pueblo). Technology Integration and Curriculum Enhancement into Higher Education Learning Environment. Proposal Development Consultant, 2000.
Jefferson County Library System (Lakewood), 1999-2000.
Southeastern BOCES (Lamar, CO). Distance Learning Curriculum Content Development Project. Proposal Development Consultant, 1998-2004.
Cheyenne Mountain School District 12 (Colorado Springs, CO). Technology Integration into Elementary Writing Curriculum Project. Proposal Development Consultant, 1998.
Telecommunications Infrastructure Fund Board Round #2 Application, 1997. Technical assistance to the following: La Villa (Texas) Independent School District; Mirando City (Texas) Independent School District; Monte Alto (Texas) Independent School District; San Isidro (Texas) Independent School District.
Telecommunications Infrastructure Fund Board Round #1, 1996. Technical assistance to the following: Brownsville (Texas) Independent School District; Donna (Texas) Independent School District; Edinburg (Texas) Consolidated Independent School District; Harlingen (Texas) Consolidated Independent School District; Jim Hogg County Independent School District (Hebbronville, Texas); La Feria (Texas) Independent School District; La Joya (Texas) Independent School District; La Villa (Texas) Independent School District; Los Fresnos (Texas) Consolidated Independent School District; Progreso (Texas) Independent School District; Raymondville (Texas) Independent School District; Rio Hondo (Texas) Independent School District; San Benito (Texas) Independent School District; Sharyland Independent School District (Mission, Texas); Weslaco (Texas) Independent School District; Zapata (Texas) County Independent School District.
South Texas Community College (McAllen). Strategy Development to Meet the Technology Instructional Needs for Vocational, School-To-Work and Academic Programs, 1994-2000. Development Consultant.
Donna (Texas) Independent School District. Planning for the Infusion of Technology in Middle Schools Serving High At-Risk Students, 1994-1995. Research Associate.
Pettus (Texas) Independent School District. Planning for District-wide Automation in School Library Media Centers: Preparation of Data, and CD-ROM Hardware/Software Configuration Evaluation, 1994. Principal Investigator.
Fort Bend Independent School District (Sugar Land, TX). Planning for District-wide Automation in School Library Media Centers, Preparation of Data, and CD-ROM Hardware/Software Configuration Evaluation, 1994-1995. Principal Investigator.
Northern Waters Library Services (Ashland, WI). Professional Consulting Services to Make Recommendations on the Development of System-Wide Efforts of the Northern Waters Library Service, 1988-1989. Research Associate.
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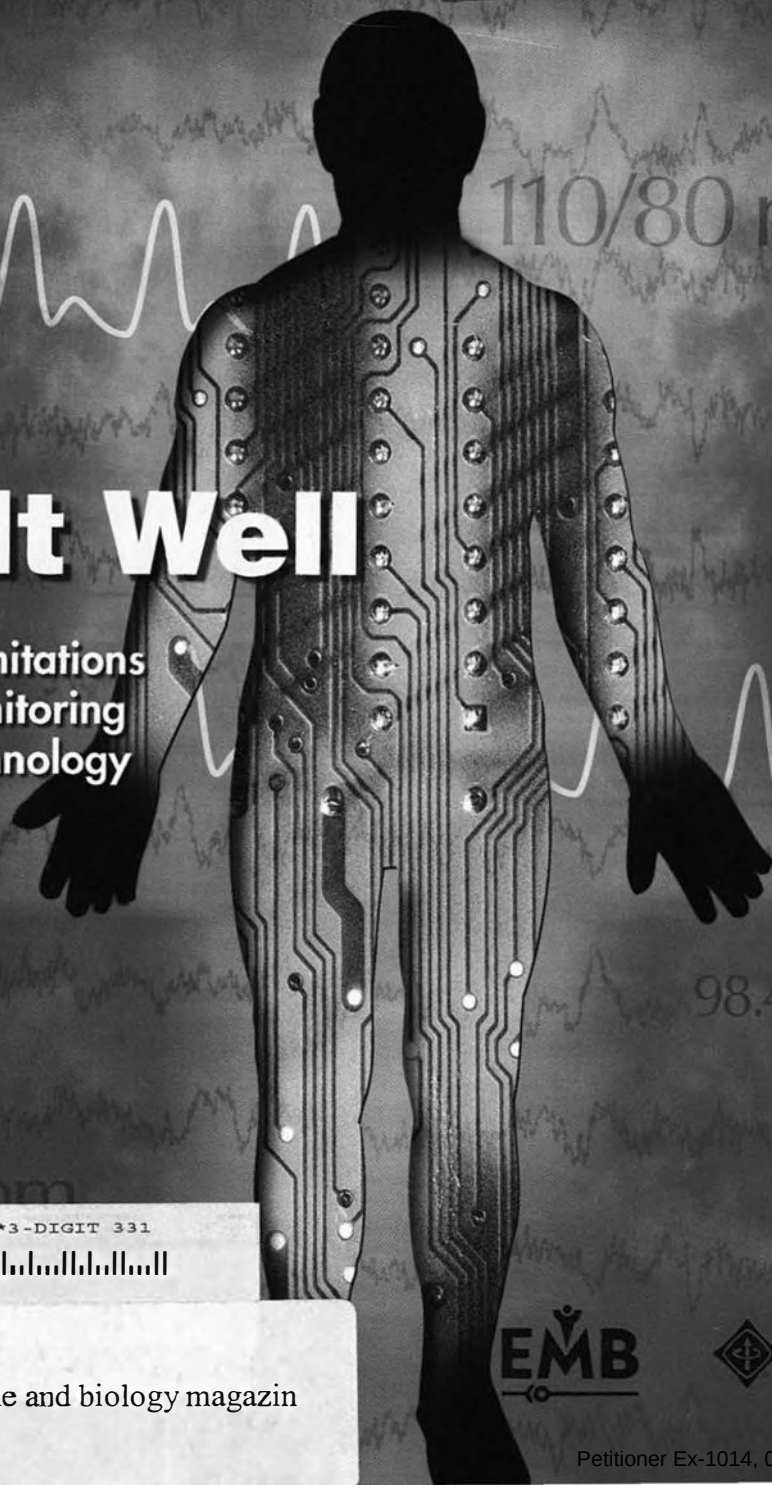
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Wear It Well

Overcoming the Limitations
of Ambulatory Monitoring
with Wearable Technology



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Impact of Wearable Technology



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Mobile Monitoring with Wearable Photoplethysmographic Biosensors

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Technical and Clinical Aspects of a Ring Sensor for Ambulatory, Telemetric, Continuous Health Monitoring in the Field, in the Hospital, and in the Home

Wearable biosensors (WBS) will permit continuous cardiovascular (CV) monitoring in a number of novel settings. Benefits may be realized in the diagnosis and treatment of a number of major diseases. WBS, in conjunction with appropriate alarm algorithms, can increase surveillance capabilities for CV catastrophe for high-risk subjects. WBS could also play a role in the treatment of chronic diseases, by providing information that enables precise titration of therapy or detecting lapses in patient compliance.

WBS could play an important role in the wireless surveillance of people during hazardous operations (military, fire-fighting, etc.), or such sensors could be dispensed during a mass civilian casualty occurrence. Given that CV physiologic parameters make up the "vital signs" that are the most important information in emergency medical situations, WBS might enable a wireless monitoring system for large numbers of at-risk subjects. This same approach may also have utility in monitoring the waiting room of today's overcrowded emergency departments. For hospital inpatients who require CV monitoring, current biosensor technology typically tethers patients in a tangle of cables, whereas wearable CV sensors could increase inpatient comfort and may even reduce the risk of tripping and falling, a perennial problem for hospital patients who are ill, medicated, and in an unfamiliar setting.

On a daily basis, wearable CV sensors could detect a missed dose of medication by sensing untreated elevated blood pressure and could trigger an automated reminder for the patient to take the medication. Moreover, it is important for doctors to titrate the treatment of high blood pressure, since both insufficient therapy as well as excessive therapy (leading to abnormally low blood pressures) increase mortality. However, healthcare providers have only intermittent values of blood pressure on which to base therapy decisions; it is possible that continuous blood pressure monitoring would permit enhanced titration of therapy and reductions in mortality. Similarly, WBS would be able to log the physiologic signature of a patient's exercise efforts (manifested as changes in heart rate and blood pressure), permitting the patient and healthcare provider to assess compliance with a regimen proven to improve health outcomes. For patients with chronic cardiovascular disease, such as heart failure, home monitoring employing WBS may detect exacerbations in very early (and

often easily treated) stages, long before the patient progresses to more dangerous levels that necessitate an emergency room visit and costly hospital admission.

In this article we will address both technical and clinical issues of WBS. First, design concepts of a WBS will be presented, with emphasis on the ring sensor developed by the author's group at MIT. The ring sensor is an ambulatory, telemetric, continuous health-monitoring device. This WBS combines miniaturized data acquisition features with advanced photoplethysmographic (PPG) techniques to acquire data related to the patient's cardiovascular state using a method that is far superior to existing fingertip PPG sensors [1]. In particular, the ring sensor is capable of reliably monitoring a patient's heart rate, oxygen saturation, and heart rate variability. Technical issues, including motion artifact, interference with blood circulation, and battery power issues, will be addressed, and effective engineering solutions to alleviate these problems will be presented. Second, based on the ring sensor technology the clinical potentials of WBS monitoring will be addressed.

WBS System Paradigm

For novel healthcare applications to employ WBS technology, several system criteria must be met. The WBS hardware solution must be adequate to make reliable physiologic measurements during activities of daily living or even more demanding circumstances such as fitness training or military battle. There must exist data processing and decision-making algorithms for the waveform data. These algorithms must prompt some action that improves health outcomes. Finally, the systems must be cost effective when compared with less expensive, lower technology alternatives.

WBS Design Paradigm

The monitoring environments for out-of-hospital, wearable devices demand a new paradigm in noninvasive sensor design. There are several design requirements central to such devices. Compactness, stability of signal, motion and other disturbance rejection, durability, data storage and transmission, and low power consumption comprise the major design considerations. Additionally, since WBS devices are to be worn without direct doctor supervision, it is imperative that they are simple to use and comfortable to wear for long periods of time. A challenge unique to wearable sensor design is the

WBS solutions, in various stages of technologic maturity, exist for measuring established cardiopulmonary "vital signs": heart rate, arterial blood pressure, arterial oxygen saturation, respiratory rate, temperature, and even cardiac output.

trade-off between patient comfort, or long-term wearability, and reliable sensor attachment. While it is nearly needless to say that WBS technology must be safe, it should be noted that there have been tragic reports of serious injury resulting from early home monitoring technology [2]. Evolving regulatory guidelines for hospital and home monitoring technology can be found in the *U.S. National Fire Protection Association Health Care Facilities Handbook*.

At the same time, the physiologic information generated by WBS technology must trigger some appropriate system action to improve health outcomes. Abnormal states must be efficiently recognized while false alarms are minimized. This requires carefully designed WBS devices, as well as innovative postprocessing and intelligent data interpretation. Postprocessing of sensor data can improve usability, as illustrated by recent improvements in pulse oximetry technology [3]-[5]. Data interpretation can occur in real time (as is necessary for detecting cardiovascular-related catastrophes) or offline (as is the standard-of-care for arrhythmia surveillance using Holter and related monitoring). Real-time alarm "algorithms" using simple thresholds for measured parameters, like heart rate and oxygen saturation, have demonstrated high rates of false alarms [6], [7]. Algorithms for off-line, retrospective data analysis are also in a developmental stage. Studies of novel automated "triage" software used to interpret hours of continuous noninvasive ECG data of monitored outpatients suggest that the software's diagnostic yield is not equal to a human's when it comes to arrhythmia detection [8], [9]. It will presumably require further improvements in WBS hardware, middleware, and software in order to fully exploit the promise of wearable ambulatory monitoring systems.

It is important to bear in mind the present limitations of the technology, such as reliability, system complexity, and cost, but there is a wide scope of exciting healthcare applications available for this technology, as will be discussed later in this article. WBS technology is a platform upon which a new paradigm of enhanced healthcare can be established. Considering that hardware solutions will inevitably become smaller, cheaper, and more reliable, and diagnostic software more sophisticated and effective, it seems more a matter of when cost effectiveness will be achieved for WBS solutions, not if.

Available WBS Monitoring Modalities

WBS solutions, in various stages of technologic maturity, exist for measuring established cardiopulmonary "vital signs": heart rate, arterial blood pressure, arterial oxygen saturation, respiratory rate, temperature, and even cardiac output. In addition,

there are numerous WBS modalities that can offer physiologic measurements not conventional in contemporary medical monitoring applications, including acoustic sensors, electrochemical sensors, optical sensors, electromyography and electroencephalography, and other bioanalytic sensors (to be sure, some of these sensors have well-established medical utility, but not for automated surveillance). These less established WBS modalities are outside the scope of this review.

Wearable electrocardiogram systems represent the most mature WBS technology. Holter and related ambulatory electrophysiologic monitoring solutions have established utility in the diagnosis of cardiac arrhythmias. There has been substantial examination of this technology in the medical literature, with excellent reviews available [10]. Temperature is technically trivial to measure using WBS, but the continuous monitoring of body temperature is only a soft surrogate for perfusion, and it lacks established utility outside of traditional clinical settings [11], [12]. There is not a satisfactory ambulatory solution for cardiac output measurement; it has been shown that cardiac output can be extracted from thoracic bioimpedance measurements, although speaking and irregular breathing, as well as posture changes and ambulation, can corrupt this signal. In the future, bioimpedance is likely to prove a powerful WBS modality, since the signal carries information about pulsatile blood volumes, respiratory volumes, intracellular and extracellular fluid balances, and has been shown to enable tomographic imaging. Respiration can be measured using bioimpedance, chest wall geometry, and acoustic means. While the basic sensor technology exists for monitoring respiratory rate, it requires the conversion of a continuous waveform into an integer (breaths per unit time), or the imprecise conversion of the measured parameter into an estimated volumetric rate (liters of gas per unit time).

Ambulatory systems for arterial blood pressure measurement exist. The portapres, employing the volume clamp technique for measuring ABP, offers a continuous waveform. The technology encumbers a finger and the wrist of the subject, is somewhat uncomfortable, and requires some expertise to set up for a subject (for instance, the finger cuff size must be carefully matched to the finger). A more common WBS solution for 24-hour monitoring of ABP involves a portable version of the common oscillometric cuff that fits around the upper arm. This solution requires that the patient keep the monitored arm immobile while the cuff inflates for measurements. By report, this solution has been known to interfere with the sleep and other activities of monitored subjects (and has been reported to cause bruising of the arm at the cuff site) [13].

No fully satisfactory WBS solution exists for ABP monitoring. Because this physiologic parameter has been the cornerstone of many decades of clinical and physiology practice, it will be important to develop future WBS solutions for monitoring ABP. It is also worth investigating surrogate measures of ABP that prove easier to measure, such as pulse wave velocity (which correlates well with degree of hypertension [14], [15]) and the second-derivative of the photoplethysmograph. This article focuses on a wearable ring pulse-oximeter solution, which measures the PPG as well as the arterial oxygen saturation. The PPG contains information about the vascular pressure waveforms and compliances. Efforts to extract unique circulatory information, especially an ABP surrogate, from the PPG waveform are discussed later in this article. The PPG provides an effective heart rate (measuring heart beats that generate identifiable forward-flow), useful for circulatory considerations though less useful for strict electrophysiologic considerations. For instance, the PPG signal may reveal heart rate variability, provided ectopic heart beats, which corrupt the association with autonomic tone, can be excluded.

Development of a Wearable Biosensor—The Ring Sensor

Technical Issues of PPG Ring Sensors

Central to the ring sensor design is the importance of long-term wearability and reliable sensor attachment. Since continuous monitoring requires a device that must be noninvasive and worn at all times, a ring configuration for the sensor unit is a natural choice. Because of the low weight and

small size, rings are generally worn without removal more often than watches. Additionally, recent studies have indicated that the finger is one of the best places for WBS sensor attachment [16]. The primary vasculature of the finger is located near the surface and therefore makes it optimal for monitoring arterial blood flow using noninvasive optoelectronic sensors. Thus, a ring is ideal for long-term measurements. As will be illustrated in the following sections, the development of the ring sensor has stressed first an understanding of and then the subsequent elimination of front-end signal artifacts. By implementing a mechanical design that is sensitive to the true causes of signal corruption, significant improvements in overall signal quality can be achieved and sensor effectiveness for various environments can be improved.

Figure 1 shows the typical waveform of a photoplethysmograph signal obtained from a human subject *at rest*. The signal comprises a large segment of dc signal and a small-amplitude ac signal. The dc component of photon absorption results from light passing through various nonpulsatile media, including tissue, bones, venous blood, and nonpulsatile arterial blood. Assuming that these are kept constant, a bandpass filter can eliminate the dc component. However, wearable PPG sensors do not meet this premise since, as the wearer moves, the amount of absorption attributed to the nonpulsatile components fluctuates. Power spectrum analysis reveals that this motion artifact often overlaps with the true pulse signal at a frequency of approximately 1 Hz. Therefore, a simple noise filter based on frequency separation does not work for PPG ring sensors to eliminate motion artifact.

Furthermore, wearable PPG sensors are exposed to diverse ambient lighting conditions, ranging from direct sunlight to flickering room light. In addition, wearable PPG sensors must be designed for reduced power consumption. Carrying a large battery pack is not acceptable for long-term applications. The whole sensor system must run continually using a small battery. Several ways to cope with these difficulties are:

- secure the LEDs and the photodetector (PD for short) at a location along the finger skin such that the dc component may be influenced less by the finger motion
- modulate the LEDs to attenuate the influence of uncorrelated ambient light as well as to reduce power consumption
- increase the amplitude of the ac component so that the signal-to-noise ratio may increase
- measure the finger motion with another sensor or a second PD and use it as a noise reference for verifying the signal as well as for canceling the disturbance and noise.

In the following sections these methods will briefly be discussed, followed by specific sensor designs and performance tests. There are other techniques for reducing motion artifact for general-purpose PPG. These, however, are mostly signal processing techniques applicable to PPG intended for short-term use. The motion artifact problem we are facing in wearable PPG design is different in nature; the source signal quality must be improved before applying signal processing. Therefore, the focus must be placed on basic sensor design.

Techniques for Reduced Motion Artifact

Sensor Arrangement

The location of the LEDs and a PD relative to the finger is an important design issue determining signal quality and robustness against motion artifact. Figure 2 shows a cross-sectional

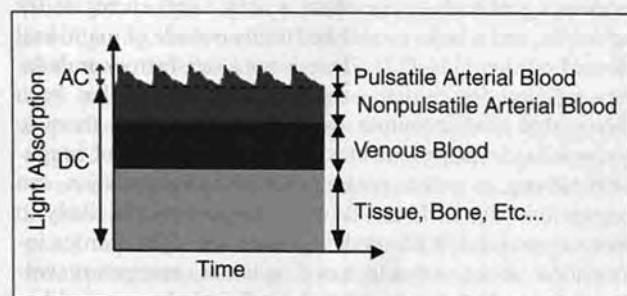


Fig. 1. Illustrative representation of the relative photon absorbance for various sections of the finger. The dc component is significantly larger than the ac component.

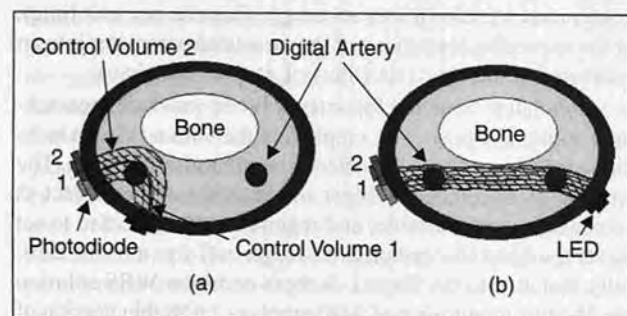


Fig. 2. (a) For the reflective illumination method, movement of the photodiode relative to the LED (position 1 to position 2) leads to a photon path that no longer contains the digital artery. (b) For the transmittal illumination method, movement of the photodetector relative to the LED still contains photon paths that pass through the digital artery.

view of the finger with the ring sensor. The LEDs and PD are placed on the flanks of the finger rather than the dorsal and palmar sides. These locations are desirable for two reasons:

- ▶ both flanks of fingers have a thin epidermal tissue layer through which photons can reach the target blood vessels with less attenuation
- ▶ the digital arteries are located near the skin surface parallel to the length of the finger.

It should be noted that an arterial pulsation is not only greater in magnitude than cutaneous pulsations but is also less susceptible to motion due to the naturally higher internal pressure. While the capillary collapses with a small external pressure on the order of 10–30 mmHg, the artery can sustain an external pressure up to 70–80 mmHg [17], [18]. Therefore, light static loads, such as contact with the environment, may not disturb the arterial pulsation.

For these reasons, at least one optical device, either the PD or the LED, should be placed on one lateral face of the finger near the digital artery. The question is where to place the other device. Figure 2 shows two distinct cases. One case places both the PD and the LED on the same side of the finger-base, and the other places them on opposite sides of the finger. Placing both the PD and the LED on the same side creates a type of reflective PPG, while placing each of them on opposite sides makes a type of transmittal PPG. In the figure the average pathway of photons is shown for the two sensor arrangements. Although the exact photon path is difficult to obtain, due to the heterogeneous nature of the finger tissue and blood, a banana-shaped arc connecting the LED and PD, as shown in the figure, can approximate its average path [19]. Although these two arrangements have no fundamental difference from the optics point of view, their practical properties and performance differ significantly with respect to motion artifact, signal-to-noise ratio, and power requirements [20]–[22].

Reflective PPG needs more secure attachments of the LED and PD to the skin surface, when compared to transmittal PPG. Once an air gap is created between the skin surface and the optical components due to some disturbance, a direct optical path from the LED to the PD may be created. This direct path exposes the PD directly to the light source and consequently leads to saturation. To avoid this short circuit, the LED light beam must be focused only in the normal direction, and the PD must also have a strong directional property (i.e., polarity), so that it is sensitive to only the incoming light normal to the device surface. Such strong directional properties, however, work adversely when a disturbance pressure acts on the sensor bodies, since it deflects the direction of the LED and PD leading to fluctuations in the output signal. As a result, reflective PPG configurations are more susceptible to disturbances.

In contrast, transmittal PPG configurations do not have the short circuit problems, since the LED and PD are placed on the opposite sides of the finger; no direct path through the air can be

created. Additionally, this design allows us to use devices having a weak polarity, which is, in general, more robust against disturbances. Furthermore, transmittal PPG is less sensitive to local disturbances acting on the finger, since the LED irradiates a larger volume of the finger. In the transmittal PPG configuration, the percentage of the measured signal does not significantly change although some peripheral capillary beds are collapsed. The percentage change is greater for reflective PPG, since this volume is smaller.

Figure 3 shows an experimental comparison between transmittal and reflective PPGs. Two sets of PPG sensors, one reflective and one transmittal, were attached to the same finger. Both were at rest initially, and then shaken. The transmittal PPG was quite stable, while the reflective PPG was susceptible to the motion disturbances.

Lighting Modulation

As is the case with most other WBS technologies, on-board power is an extremely important design consideration and is often the limiting factor in design size, function, and flexibility.

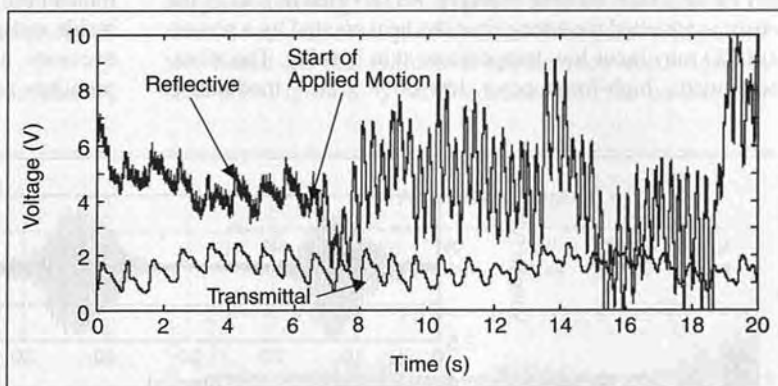


Fig. 3. Corruption of a continuous PPG waveform during the application of a simple chopping motion. Note that while the motion corrupts the reflective sensor signal, the transmittal sensor signal remains unaffected.

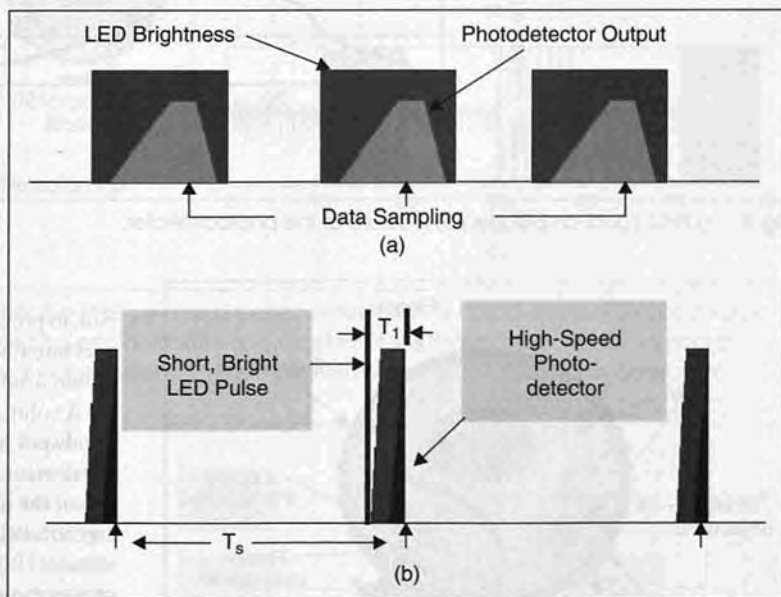


Fig. 4. (a) The slow response time of the photodetector meant that the LED had to be modulated at lower frequencies for data sampling. (b) A faster photodetector response time makes it possible to increase the modulation frequency of the LED.

To keep the overall unit small, the ring sensor design demands a power source that is no larger than the coin batteries used for wristwatches. Despite the superior stability and robustness, transmittal PPG consumes more power. According to the Lambert-Beer law, the brightness decreases exponentially as the distance from the light source increases. Transmittal PPG must have a powerful LED for transmitting light across the finger. This power consumption problem can be solved with a lighting modulation technique using high-speed devices. Instead of lighting the skin continually, the LED is turned on only for a short time, say 100 ~ 1000 ns, and the signal is sampled within this period. High-speed LEDs and PDs, which have become available at low cost in recent years, can be used for this purpose. Figure 4 shows a schematic of high-frequency, low-duty cycle modulation implemented to minimize LED power consumption. Utilizing fast rise-time optical detectors, it is possible to incorporate a modulation frequency of 1 kHz with a duty ratio of 0.1%, a theoretical power usage that is 1,000 times less than conventional full-cycle modulation methods [23].

Use of a strong light source needed for transmittal PPG may cause a skin-burning problem. As reported in [24], if the sensor is attached for a long time the heat created by a powerful LED may incur low-temperature skin burning. The aforementioned high-frequency, low-duty rate modulation

described above is an effective method for preventing these types of injuries.

In addition to saving power, the modulation of LED lighting provides an effective means for reducing ambient light disturbances. Reading the PD output while the LED is turned off yields the baseline PPG level attributed to the ambient light alone. Subtracting this reading from the one acquired with the LED illuminated gives the net output correlated with the LED lighting. More sophisticated modulation schemes can be applied by controlling the LED brightness as a periodic time function. Computational power requirements often prohibit complex modulation, however. Design trade-offs must be considered to find the best modulation scheme.

Transmural Pressure

Increasing the detected amplitude of arterial pulsations (i.e., the ac component in Figure 1) improves the signal-to-noise ratio of PPG. It is well understood that the application of an external pressure on the tissue surrounding the artery will increase the pulsatile amplitude. Such a pressure reduces the transmural pressure; that is, the pressure difference between inside and outside of the blood vessel. The pulsatile amplitude becomes a maximum when the transmural pressure approaches zero, since the arterial compliance becomes maximal with zero transmural pressure [25], [26]. Applying a pressure, however, may interfere with tissue perfusion. Since the device is worn for long periods of time, the pressure must be kept such that it does not exceed levels that could damage other vasculature [27]. Thus, the mechanism for holding the LED and PD must be designed such that it provides a safe level of continuous pressure, well below the established clinical threshold.

Figure 5 shows the pulsatile amplitude of a finger base PPG for varied pressures generated by a finger cuff. As the cuff pressure increases, the PPG amplitude increases until it reaches a maximum. As the pressure keeps increasing further, the amplitude decreases due to occlusion of the blood vessels. The cuff pressure yielding the largest PPG amplitude, generally near the mean arterial pressure [28], is too high to apply for a long period of time.

But, to prevent the capillary beds from being collapsed, the cuff pressure must be on the order of 10 mmHg, which is too low to obtain a sufficient PPG amplitude.

A solution to this problem is to apply the pressure only at a local spot near the photodetector. When using a cuff or any of the devices that provide uniform surface pressure onto the finger or the arm, it constricts the blood vessels, thus limiting or significantly impeding the amount of blood supplied downstream. However, by providing a local, noncircumferential increase in pressure near the sensor's optical components, it is possible to amplify the plethysmograph waveform while avoiding the potentially dangerous situation of long-term flow obstruction. As shown in Figure 6, the tissue pressure in the vicinity of one of the arteries can be increased with use of a

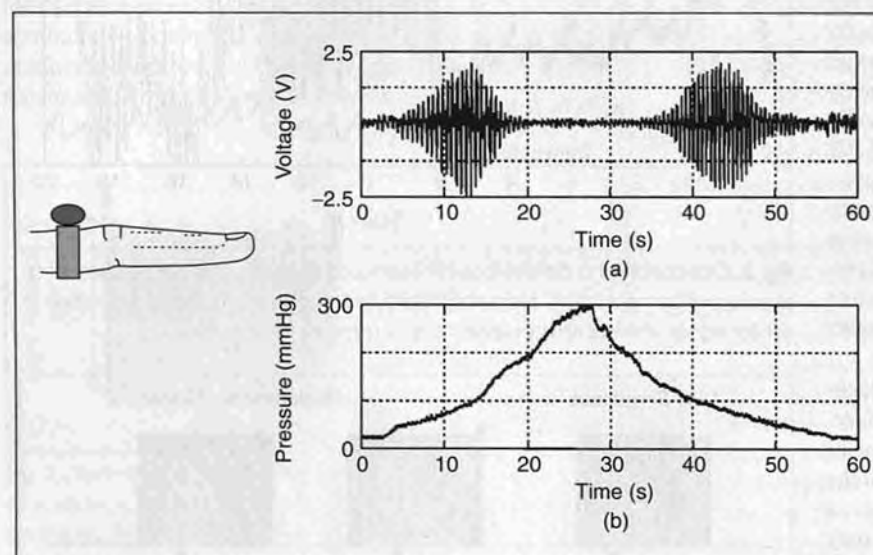


Fig. 5. (a) PPG signal amplitude. (b) Pressure at the photodetector.

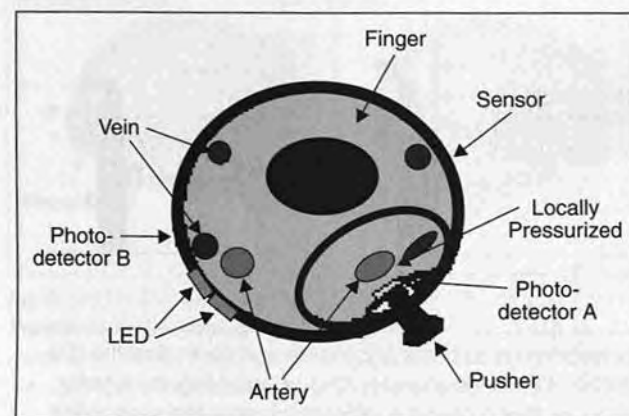


Fig. 6. The schematic of a locally pressurized sensor band.

special mechanism pushing Photodetector A toward the skin. This mechanism, which is attached to the sensor band, would change the pressure distribution such that the transmural pressure of one of the arteries could be high enough to obtain a large pulsatile signal while keeping the pressure low elsewhere to allow for sufficient blood perfusion. As long as the pressurized area is small enough to perfuse it from the surrounding tissue, the local pressurization causes no major complication although the pressure is applied for many days.

Noise Reference

Wearable sensors are to be used with no supervision by medical professionals, as mentioned previously. It is therefore important to monitor whether signals have been obtained under proper conditions. Although the techniques described above are effective for reducing motion artifact, it is still necessary to verify the signal before sending it out for clinical diagnosis. Questionable data can be rejected if the wearable sensor has a means to monitor the hand motion and other sources of disturbances. In the following section, a novel method for detecting finger motion for the verification of signal reliability as well as for recovering the correct signal from a distorted signal will be described.

The motion of the finger can be measured with an accelerometer attached to the body of the ring. MEMS accelerometers are now available at low cost, but they are still too bulky and/or consume too much power to use for the ring sensor. There is no commercially available product satisfying both the power limit and form factor requirements. Instead of using a standard sensor dedicated for motion measurement, the PPG optical sensor can be used as a motion sensor. The fact that PPG is susceptible to motion disturbances implies that the sensor has the potential to be an effective detector of motion. With minor modifications to the original PPG design, the PPG motion detector would have a high sensitivity to detect the nonpulsatile dc component shown in Figure 1. The techniques developed for reducing motion artifact are to be reversed in order to increase the motion sensitivity. First, the reflective PPG arrangement should be used, so the distance between the LED and PD must be shortened. The pressure should be kept low so that less pulsatile signals may be observed. The location of the PD should be away from the arteries and close to a vein instead. In addition, the wavelength of the LED should be selected such that it is more sensitive to the reduced hemoglobin (i.e., approximately 660 nm), since the nonpulsatile vein is filled mostly with the reduced hemoglobin. Figure 6 shows a desirable location for the photodetector detecting the finger motion. Photodetector B in the figure is placed close to the LED as well as to a vein on the low-pressure side. Figure 7 shows an experimental result of the reflective PPG exposed to hand motion. It is clear that the PPG signal has a strong correlation with the acceleration of the hand.

The motion detector can be used not only for monitoring the presence of motion but also for canceling noise. By using PD-B as a noise reference, a noise cancellation filter can be built to eliminate the noise of PD-A that correlates with the noise reference signal. Assuming that the hemodynamic process observed by PPG is stationary and that the noise is additive, adaptive noise canceling methods, such as the classical Widrow method [29], can be applied in order to recover the true pulsation signal from corrupted waveforms. As shown in Figure 8, the noise-canceling filter combines two sensor signals; one is the main signal captured by PD-A and the other is the noise reference obtained by PD-B. The main signal mostly consists of the true pulsatile signal, but it does contain some noise. If we know the proportion of the noise contained in the main signal, we can generate the noise of the same magnitude by attenuating the noise reference signal and then subtract the noise from the main signal to recover the true pulsatile signal. If the noise magnitude is not known a priori, it must be determined adaptively during the measurement. Various algorithms for adaptive filtering can be applied to tune the filter in real time. Some can determine optimal filter gains and parameters based on the evaluation of the recovered signal, as shown in Figure 8 by the feedback from the output to the

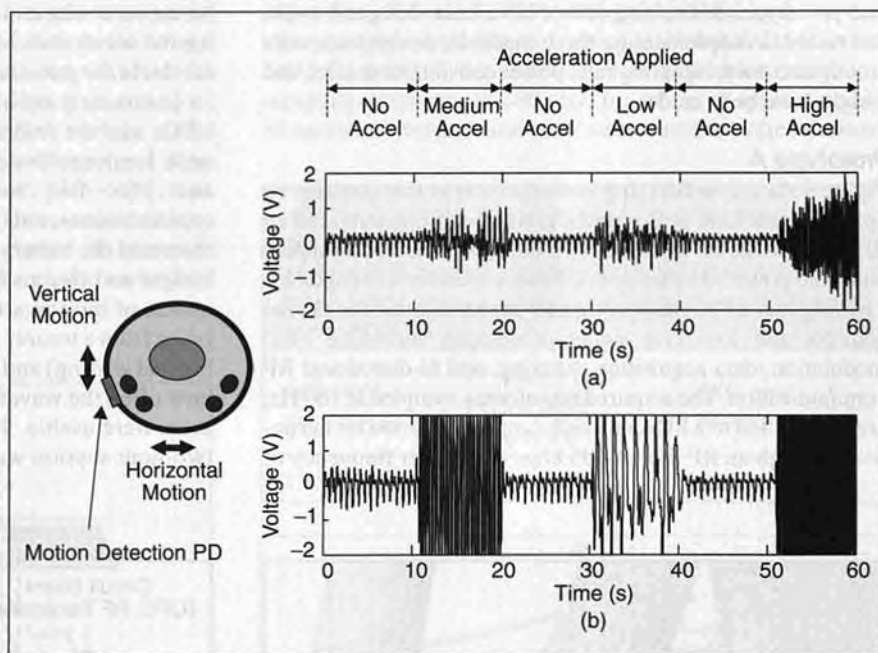


Fig. 7. Reflective PPG used as a motion detector: PPG output has a strong correlation with the vertical and horizontal acceleration of the finger. (a) Photoplethysmogram with vertical acceleration. (b) Photoplethysmogram with horizontal acceleration.

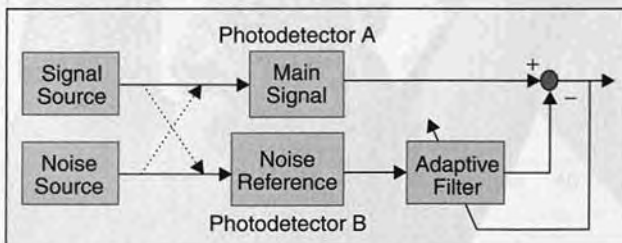


Fig. 8. Block diagram of adaptive noise cancellation using second PPG sensor as noise reference.

Since continuous monitoring requires a device that must be noninvasive and worn at all times, a ring configuration for the sensor unit is a natural choice.

adaptive filter block. Details of this adaptive filtering method are beyond the scope of this article. The dual photodetector design shown in Figure 6 provides both main signal and noise reference that are distinct. This allows us to implement noise-canceling filters effectively despite complex motion artifact.

Prototyping and Results

Based on the methodologies for reducing motion artifact, several prototypes of the ring sensor have been designed, built, and tested. In implementing these methods, design trade-offs among accuracy, sampling rate, power consumption, size, and weight have been made.

Prototype A

Figure 9 shows the first ring sensor prototype that contains an optical sensor unit, analog and digital processing units, and an RF transmitter, all of which are encapsulated in a compact body and powered by a tiny cell battery used for wristwatches. The ring has a PIC microcomputer performing all the device controls and low-level signal processing, including LED modulation, data acquisition, filtering, and bi-directional RF communication. The acquired waveforms, sampled at 100 Hz, are transmitted to a PDA or a cellular phone carried by the patient through an RF link of 105 kbps at a carrier frequency of

915 MHz. The cellular phone then accesses a Web site for data storage and clinical diagnosis.

An obvious source of signal corruption results from the direct interaction of the sensor unit with the wearer's surrounding environment; e.g., holding objects, touching surfaces, etc. Thus, the body of the ring must separate the sensor unit in order to decouple the sensor unit from these interactions. To this end, a double ring configuration was designed and implemented, as shown in Figure 10. The disturbance force is born by the outer ring and is not transmitted to the inner ring holding the sensor unit. Moreover the outer ring serves as an optical shield for protecting the sensor unit from the ambient light.

In this early development, the power consumption of the LEDs and the imbedded CPU clock were a major bottleneck limiting the design. The distance between the LEDs and PDs had to be shortened for power saving considerations, and the CPU clock was minimized in order to extend the battery life to a few weeks. See [30] for power budget and design details. To evaluate the overall performance of motion artifact resistance, data were continually taken from a wearer performing daily office work (e.g., typing and writing) and the acquired data were examined to see how often the waveforms were corrupted and how many of them were usable. The result was that 35% of the data in a two-hour session was not corrupted and usable.



Fig. 9. First prototype ring sensor with RF transmitter powered by a coin-size cell battery.

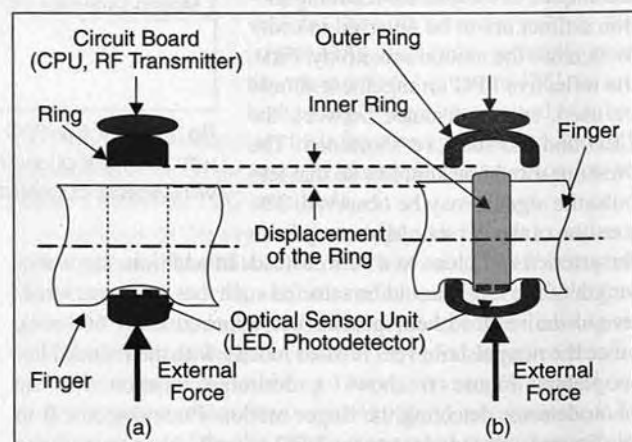


Fig. 10. Dislocation of ring sensors due to external load. (a) Traditional single-body design under external force. (b) New isolating double ring sensor under external force [31].

Continuous monitoring also enables caregivers to gather accurate data about patients' home physiologic states, since patients measuring their own blood pressure may leave out unsatisfactory numbers.

Prototype B

To improve motion artifact resistance and accuracy, a transmittal PPG ring sensor, Prototype B, has been built and field-tested. Prototype B has high-speed optical devices enabling the lowering of the LED duty rate to 1/1,000. The LED used is 6.7 times brighter than that of Prototype A, while the resultant power consumption is 173 times smaller than before. The sensor band was redesigned with the use of bio-compatible elastic materials to better hold the LED's and PD's, maintain a proper level of pressure, optically shield the sensor unit, and secure the contact with the skin consistently in the face of finger motion (see Figure 11). As a result, the waveform of this transmittal PPG was quite stable. Figure 3 presented earlier is the experiment of Prototype B. Note that the transmittal PPG (Prototype B) signal did not collapse even when the hand was shaken. Additionally, the analog filtering circuit was optimized for quality of signal. These modifications greatly improved the ability of the device to measure traditionally difficult variables such as heart rate variability (Table 1, Figure 12).

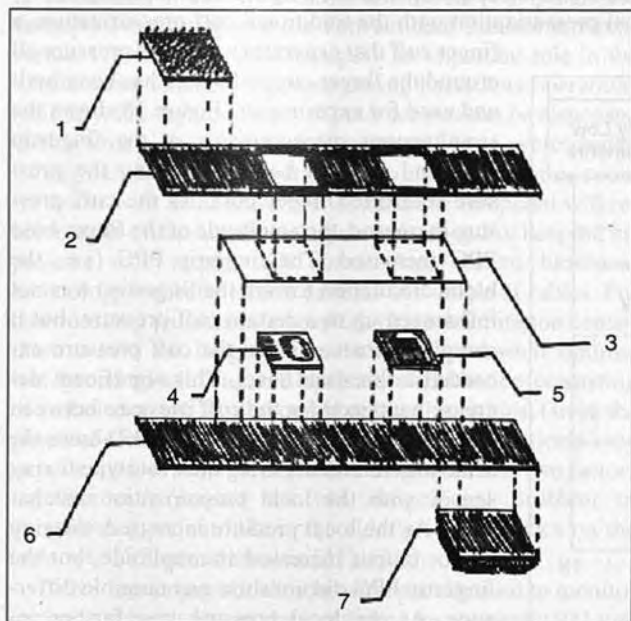


Fig. 11. Redesigned sensor band that protects optical components from direct contact with skin and hides wires from outside environment.

This Prototype B ring sensor was recently given IRB approval for patient testing in the Pulmonary Function Testing Laboratory at the Massachusetts General Hospital. Due to hospital regulations a tethered version of Prototype B was benchmarked with a Nellcor-395 fingertip pulse oximeter for motion artifact resistance and oxygen saturation measurements during patient motion (defined to be motion while riding a stationary bicycle). Each patient voluntarily participated in the study and was given the opportunity to end the testing at any point, if desired. Plethysmographs from both devices were sampled and recorded using a National Instruments DAQ Card-6024E for PCMCIA data acquisition board at a sampling frequency of 1000 Hz, for a time of approximately 30 minutes. Oxygen saturation measurements were addition-

TABLE 1. RMS error (beats/min) of the pulse rates from the ring sensor B compared with those from EKG and Nellcor PPG devices. Significant improvements have been made when comparing the ring sensor/EKG error to the EKG/Nellcor error.

EKG and Ring Sensor B	Nellcor PPG and Ring Sensor B	EKG and Nellcor PPG
1.43	3.15	2.88

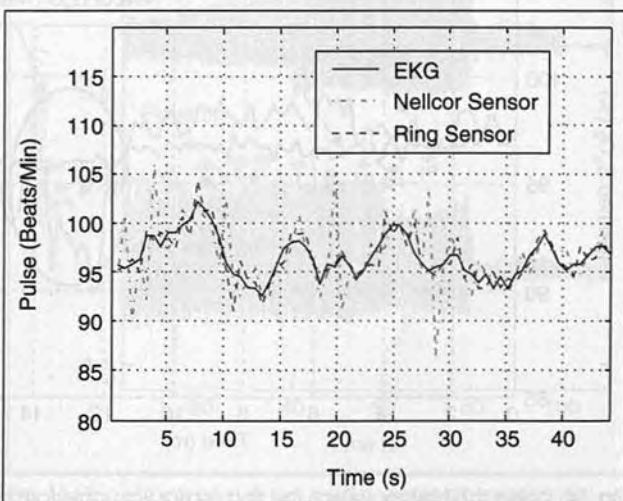


Fig. 12. Beat-to-beat pulse rate of Prototype B ring sensor benchmarked with EKG and FDA-approved fingertip PPG by Nellcor.

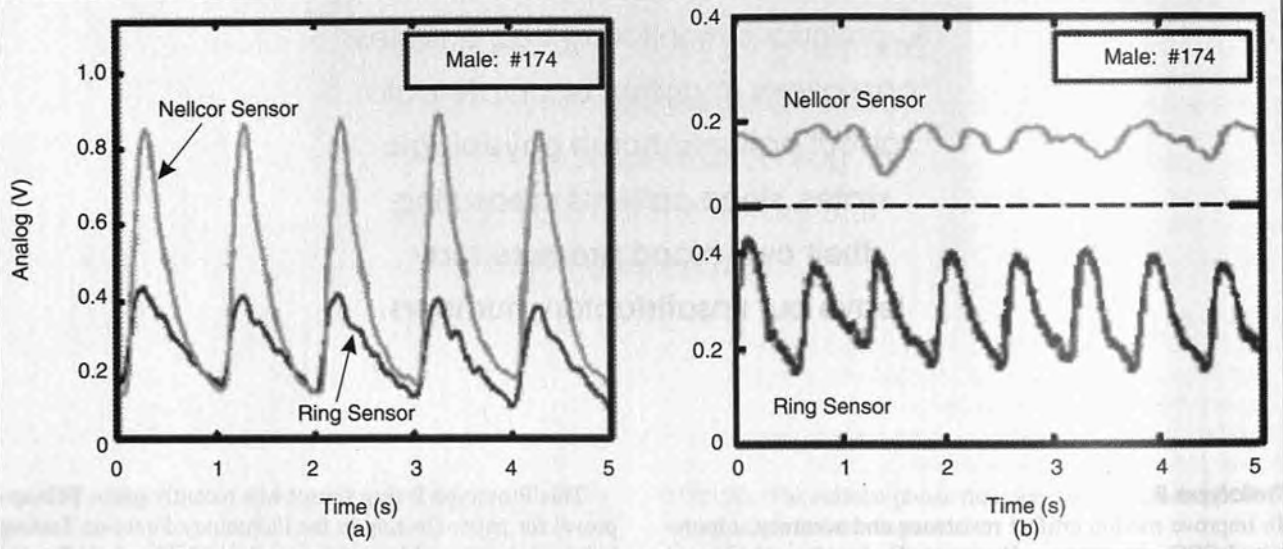


Fig. 13. Representative example of PPG benchmarking data acquired while (a) patient was at rest and (b) patient was riding a bicycle against a graded resistance.

ally benchmarked with both the Nellcor sensor and with arterial blood gas samples analyzed by a CO-Oximeter. The ring sensor data used for comparison were the raw, unprocessed sensor data. No additional postprocessing algorithms were used to improve the quality of the measured signals.

In general, it was found that the ring sensor and the Nellcor sensor had comparable stability and resolution while the patient was at rest. However, the ring sensor was found to have a significantly more stable signal than the Nellcor fingertip pulse oximeter while the patient was riding the bicycle (Figure 13).

In addition to added waveform stability, the ring sensor demonstrated superior performance under motion conditions while monitoring the patient's oxygen saturation as is shown in Figure 14. Further, each patient was asked to fill out a survey before, during, and after each trial. The survey consisted of a simple comfort rating system for the ring sensor. The pa-

tients indicated no discomfort (no worse than wearing a hat) at any time during the testing of the device.

Prototype C

The local pressurization and motion detection methods described previously have been implemented for further improvement. Figure 15 shows the schematic of the Prototype C ring sensor. Both transmittal (PD-A) and reflective (PD-B) PPGs were mounted on the sensor band. The former is placed on top of a locally pressurizing mechanism with an adjustable setscrew. The latter is mounted on the low-pressure side in order to detect motion.

To evaluate how a pressure applied to the finger base interferes with blood circulation, the blood flow toward the fingertip was measured by using Nellcor's PPG sensor attached to the fingertip. For the purpose of comparing the local pressurization with the traditional cuff pressurization, a

finger cuff that generates a uniform pressure all around the finger circumference has been built and used for experiments. Figure 16 shows the simultaneous measurements of the fingertip PPG and a finger base PPG using the pressure-controlled finger cuff. As the cuff pressure increased, the amplitude of the finger base PPG increased. The fingertip PPG (i.e., the blood circulation toward the fingertip) was not influenced up to a certain cuff pressure, but it sharply decreased when the cuff pressure exceeded a threshold level. This significant decrease happened for the cuff pressure between 80 mmHg and 120 mmHg. Figure 17 shows the same measurements using the Prototype C ring sensor with the local pressurization mechanism. As the local pressure increased, the ring sensor output increased in amplitude, but the fingertip PPG did not show any tangible difference. As the local pressure was further increased, the ring sensor output gradually decreased. The fingertip PPG did not change even for this excessive local pressure. The ex-

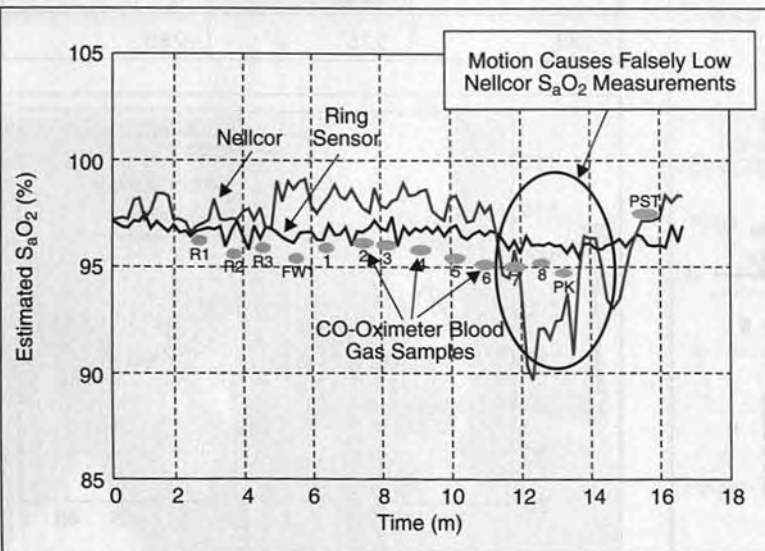


Fig. 14. Unlike the Nellcor sensor, the ring sensor was able to more accurately follow the oxygen saturation trend of the patient due to improved waveform stability during patient motion.

act value of the local pressure is not available due to difficulties of instrumentation, but the nominal pressure given by the normal force divided by the pressurized area was 120 mmHg when the maximum output amplitude was reached. Since the finger consists of a network of veins and arteries, pressurizing a small spot, 5 mm in diameter, at the finger base does not significantly affect the overall circulation within the finger.

These results clearly indicate that it is possible to achieve a design that can meet the critical, conflicting design requirements for out-of-hospital environments. By developing a thorough understanding of both the physiology of the relevant signals and the mechanisms through which these signals can be acquired, it is possible to design a wearable biosensor that can offer cost-effective, acceptable diagnostic test characteristics that are effective over a broad range of novel health applications outside of traditional clinical monitoring settings.

Survey of Applications for Ring Sensor Technology

There are a number of promising applications for PPG and pulse oximetry-related WBS technologies. Applications range from real-time catastrophe detection to management of chronic medical conditions and regimen compliance. The scope of these applications are described below, with focused consideration of surveillance for the catastrophe of Sudden Infant Death Syndrome (SIDS), as well as the long-term management of hypertension and chronic heart failure. Overall, WBS technology stands to make a major impact by taking surveillance for numerous cardiovascular/pulmonary conditions outside of traditional medical settings.

Catastrophe Detection

In one class of applications, the goal is to detect a physiologic catastrophe (meaning the development or progression of a dangerous or unstable state) and trigger a timely response that improves outcomes. WBS, in conjunction with diagnostic algorithms and some specific response (which might be human or automated in nature), stand to ameliorate physiologic catastrophes occurring outside conventional clinical environments. For instance, WBS can play an important role in the wireless surveillance of people during hazardous operations (military, fire-fighting, etc.), or such sensors can be dispensed during a mass civilian casualty occurrence. In an overcrowded Emergency Department, patients who are in the waiting room for hours with an undifferentiated medical complaint will receive state-of-the-art physiologic monitoring. For hospital inpatients who require CV monitoring, current biosensor technology typically tethers patients in a tangle of cables. For convalescing patients in a hospital, or a rehabilitation center, there would no longer be a dichotomy between optimal bed-bound monitoring and optimal rehabilitation consisting of ambulation and a full scope of physical activities. Given the physical freedom when monitored by WBS, inpatients may experience less physical deconditioning, and these two factors together may impact the not insignificant problem of dangerous inpatient falls in the elderly (an incidence on the order of 1-5% per admission [32], [33]).

WBS measuring circulation could also be used to monitor geriatric subjects living alone, offering an automatic 911 call in the event of a catastrophe and peace of mind for the subject and concerned family the rest of the time. The dissemination of new automated defibrillators for the home, such as the re-

cently FDA-approved Philips Electronics' HeartStart model, means that the general public will be increasingly able to respond to victims of life-threatening arrhythmias when such catastrophes are detected. SIDS demonstrates the potential power and liability of WBS technology implemented in a home monitoring system. SIDS, the leading cause of death in infants less than 1 year of age, afflicts several thousand infants per year in this country [34], [35]. Unfortunately, the precise pathophysiology of SIDS remains unknown, and it is likely due to a range of etiologies that cannot be distinguished post-mortem. Over 25 years ago, new initiatives were taken to implement home cardiopulmonary monitoring for high-risk infants [36], [37]. In one series, the impact of home monitoring appeared powerful, as 12 of 50 monitored high-risk infants received resuscitation for life-threatening events. At that time, though, there was a significant issue of false alarms due to imperfect technology solutions and inaccurate parental assessment of the infant's health [38], [39]. In the Collaborative Home Infant Monitoring Evaluation (CHIME) study, it was

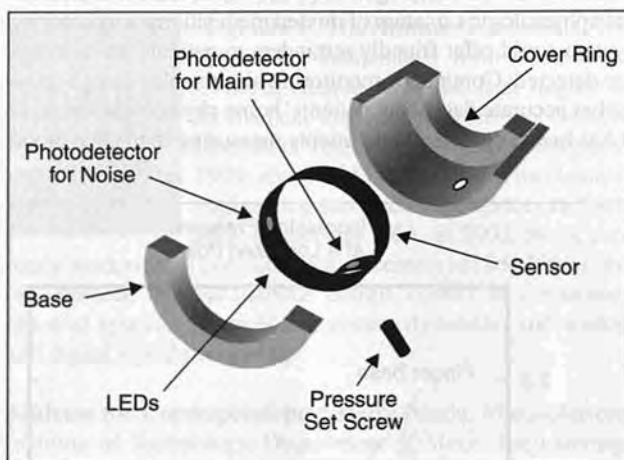


Fig. 15. The schematic of the Prototype C ring sensor.

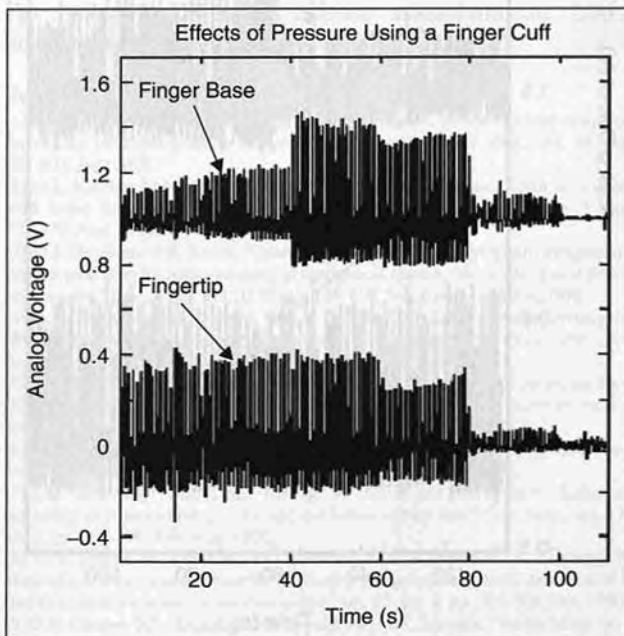


Fig. 16. The effects of cuff-induced pressure changes monitored at the fingertip and the finger base—cuff pressure changes completely occlude blood flow.

noted that apnea and bradycardia are relatively common events for healthy infants (this study of 1,079 infants was not large enough to address the impact on mortality of home monitoring on SIDS because the disease incidence is between 0.5 and 1.0 per 1,000) [40]. It seems that WBS technology might offer a powerful solution to the leading cause of death of U.S. infants, but it will require acceptable WBS hardware and diagnostic algorithms that identify endangered infants in time for their parents and/or emergency medical service to make a useful intervention. Such a system will also be judged on its rate of financially (and emotionally) expensive false alarms, since automated alarms will likely trigger expensive and stressful medical evaluations.

Chronic Medical Conditions

WBS may enable a new paradigm in the management of long-term CV disease, enhancing the titration of therapies and detecting disease progression. Moreover, it has been suggested that serious noncompliance occurs in from 30 to 60% of outpatients on a medication regimen [41], [42]. If there is a measurable physiologic signature of missed medications, a monitoring system could offer friendly reminders to patients when lapses are detected. Continuous monitoring also enables caregivers to gather accurate data about patients' home physiologic states, as it has been suggested that patients measuring their own blood

pressure may leave out unsatisfactory numbers [43]. Similarly, measurement of heart rate changes indicative of exertion might serve to track compliance with an exercise regimen, thus motivating patient adherence to an exercise regimen, given the benefits of even low-level physical activity [44]. Potential utility of long-term WBS monitoring for management of hypertension and chronic heart failure are discussed below.

Hypertension

Hypertension is a major risk factor for cardiovascular (CV) disease, and though disease prevalence is quite subject to the diagnostic criteria used, hypertension afflicts on the order of 25% of the American population [45], [46]. Currently, the diagnosis of hypertension is made using discrete values of the waveform's peak (systolic) and trough (diastolic) pressure values, measured over a small number of cycles, which are assumed to be representative of the subject's chronic vascular state. Yet an approach relying on discrete ABP measurements, especially those acquired in a clinical setting, is problematic and often inaccurate [47], [48]. Despite the magnitude of the CV risks of hypertension, present medical approaches to treating the condition have not been shown to fully reduce the risk [49], [50]. The discrete approach for measuring ABP may very well put some patients at risk for undertreatment or overtreatment with medication [51]–[54]. It is possible that there are intrinsic limitations to the discrete approach to ABP characterization.

In contrast, multiple studies have suggested the benefit of ambulatory blood pressure measurement (the ABP is measured repeatedly in the outpatient setting to produce a 24-hour time-course) as compared to standard clinic and home measurements, for risk stratification and predicting morphologic changes in the left ventricle [55]–[58]. There is evidence that treatment is more effective when titrated to ambulatory blood pressure versus conventional measurement strategies [59]. Typically, though, a cuff-based technique is employed, which limits the subject's activities or limits the reliability of the measurements when the subject is active [60], [61]. In conjunction with novel diagnostic algorithms able to analyze long time-series of data, a truly wearable ABP biosensor stands to improve the efficacy of medical treatment. As noted in section 2.2, there is presently no adequate WBS solution for this application, but it has been demonstrated that measures of arterial compliance, closely related to hypertension, can be extracted from the plethysmograph and PPG [62]–[64]. Given the potential for the Asada group's ring sensor to meet the desirable design criteria necessary for a robust WBS modality, there is reason to give future attention to the PPG and other ABP surrogates in future studies of the efficacy of ambulatory and long-term ABP monitoring.

Congestive Heart Failure Management

Another potential application for chronic surveillance using WBS is the management of heart failure. This chronic disease is characterized by episodic, acute exacerbations that frequently lead to costly inpatient admissions. In the 1990s, an average hospitalization cost approximately US\$10,000, versus US\$4,000 for average annual outpatient care expenditures [65]. By the year 2007 heart failure is projected to afflict 10 million Americans [66]. Yet most patients admitted with acute heart failure have an identifiable precipitant, and it seems reasonable to hypothesize that a majority of these precipitants

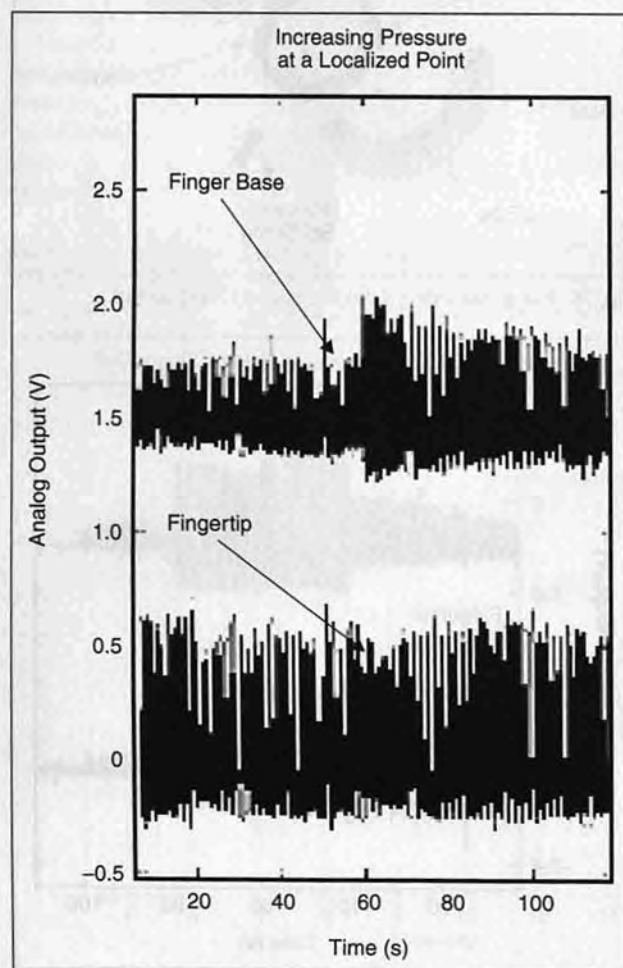


Fig. 17. The effects of local pressure changes monitored at the fingertip and the finger base—no significant change in the downstream circulation.

(such as medication noncompliance, and dietary indiscretion, accounting for about 64% of the cases in one series [67]) might be detected by continuous home monitoring well before the exacerbation necessitated the costly hospital admission. There are a constellation of clinical symptoms associated with worsening heart failure, including increased dyspnea with exertion, increased dyspnea with recumbent positioning (orthopnea or paroxysmal nocturnal dyspnea), and increasing peripheral edema. Certainly it has been recognized that management of advanced heart failure patients calls for "intensive home monitoring" [68]. Ultimately, the utility of WBS in screening for heart failure exacerbation rests in the sensitivity of the sensor measurements to identify these aforementioned abnormalities using one or multiple modalities, including oximetry, plethysmography, extremity conductance, microphony, etc. Given that WBS technology enables continuous monitoring, one specific advantage is that it allows detection of transient phenomena, such as transient hypoxia with exertion or recumbent positioning. WBS technology is an appealing potential solution to intensive home monitoring, as abnormal sensor measurements could prompt further diagnostic and therapeutic measures.



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Ex-1007

AUTOMATIC ARTIFACT REJECTION FOR EEG DATA USING HIGH-ORDER STATISTICS AND INDEPENDENT COMPONENT ANALYSIS

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ABSTRACT

While it is now generally accepted that independent component analysis is a good tool for isolating both artifacts and cognitive related activations in EEG data, there is still little consensus about criteria for automatic rejection of artifactual components and single trials. Here we developed a graphical software to semi-automatically assist experimenter in rejecting independent components and noisy single data trials based on their statistical properties. We used kurtosis to detect peaky activity distributions that are characteristic of some types of artifact and entropy to detect unusual activity patterns. EEG-LAB, a user-friendly graphic interface running under Matlab, allows the user to tune and calibrate the rejection criteria, to accept or override the suggested components and trials labeled for rejection, and to compare the results with other rejection methods.

1. INTRODUCTION

It is critical to detect artifact contamination of evoked-potential EEG data for several reasons. First, artifactual signals usually have high amplitudes. Thus, even if their distribution in the recorded EEG is sparse, they can bias evoked potential averages constructed from the data and, as a consequence, bias the results of an experiment. Rejecting artifacts is also critical when data are used in further processing to interpret brain area activity - e.g. event related spectral perturbations or Independent Component Analysis (ICA) [1].

In most current EEG software packages, single data trials are rejected when they contain out-of-bounds potential values at single electrodes. In event-related experiments, each data epoch normally represents a single experimental trial. Usually, the experimenter first subtracts a baseline - e.g., the average potential before the stimulus occurs - from each trial. Then, the experimenter chooses rejection electrodes at which potential values should not exceed some defined threshold value. The selected electrodes usually include central scalp placements which record a large portion of brain activity, parietal placements including temporal muscle artifacts and/or frontal electrodes containing blinks and eye movement artifacts. The

problem with this thresholding process is that it only takes into account low-order signal statistics (min, max). This kind of rejection might not be sufficient to detect muscle activity for instance, which typically involves rapid electromyographic (EMG) signals of moderate size. Higher order statistical properties of the EEG signals might contain more relevant information about this and other types of artifacts.

Independent Component Analysis (ICA) applied to collection of single trials EEG data has proven to be efficient for separating distinct artifactual and neural EEG processes [1]. ICA is able to separate brain activation processes or artifacts whose time waveforms are (maximally) independent of each other. For instance, eye movements and muscle activities produce specific ICA activation patterns and component maps [2][3]. While ICA is now considered an important technique for removing artifacts, there is still little consensus about the characteristics of artifact components. In this paper, we develop a framework for semi-automatic artifact rejection based on data and independent component activity statistics. We first apply these measures to the raw data. Then, we apply ICA to the data and use statistics on the independent component activities to locate and reject both artifactual data trials and artifactual components. EEG-LAB, a user-friendly graphic interface under Matlab, guides the user through this process (www.salk.edu/~arno/eeglab.html). The EEG-LAB software is based in part on the ICA/EEG toolbox of Makeig et al. (www.salk.edu/~scott/ica.html) and implements some of its functions to help the user visualize the data and make decisions about which components to reject. To test and illustrate the rejection process, we used event related EEG data from a go-nogo visual categorization task [4] (32-electrode montage, ears referenced, 1000 Hz sampling rate, 1200 target and non-targets trials per subject).

2. ARTIFACT REJECTION ON RAW DATA

Most artifacts are typically "odd" data in the sense that they are transient and unexpected events. Isolating artifacts thus involves detecting such events. To do so, we chose two measures: probability distribution and kurtosis. The probability

of a data trial activity, given the probability distribution of activity in all data trial, is a measure of the data trial's "oddness". If the probability value is low, it means that the activity values in a data trial at a given electrode are unexpected, given the probability distribution of other data trials' activity at the same electrode. To estimate the relative probability of each trial of our raw data, we first computed the observed probability (D_e) density function of all data value at each electrode e . Then, we computed the logarithm of the joint probability $J_e(i)$ of the activity values (A_i) of each single data trial i at electrode e :

$$J_e(i) = -\log\left(\prod_{x \in A_i} p_{D_e}(x)\right) \quad (1)$$

$p_{D_e}(x)$ being the probability of observing the value x in the probability distribution D_e of activity at electrode e . We used the logarithm of the joint probability for better graphic presentation of very low joint probability values. The joint probability was computed for every single data trial at each electrode.

The probability measure allows us to detect outlier trials. We might be able to spot other artifact trials based on their unusually peaky distribution of potential values. In some artifact trials, the distribution of activation is very peaky, for example a trial containing strong transient muscle activity. To measure this peakyness, we used the kurtosis of the activity values in each trial. Kurtosis is the 4th cumulant of the data – the mean being the first cumulant and the variance the second. For each trial at each electrode, the kurtosis was calculated using the following equations:

$$K = m_4 - 3m_2^2 \quad (2)$$

$$m_n = E\{(x - m_1)^n\} \quad (3)$$

where m_n is the n^{th} central moment of all activity values of the trial, m_1 the mean, and E the expectancy function (in our case the average). Typically, if the kurtosis is highly positive, the distribution of activity is peaked and sparse, and the identified data is likely to be an artifact. If the all activity values are similar, the kurtosis will be highly negative. Once more, this type of activity is not typical of true EEG signals, which reflect non-stationary processes, so low kurtosis values make us suspect the presence of artifactual data. Negative kurtosis values usually reflect AC (alternating current) or DC (direct current) artifacts, for example those induced by line or screen currents or by loose electrode contacts.

Before defining rejection thresholds for both entropy and kurtosis, we first normalized these measures (to 0-mean and standard deviation 1). We were thus able to define thresholds in terms of a number of standard deviations from the mean (figure

1). We usually used thresholds higher than 5, which means than, assuming a gaussian distribution of the true EEG activity values at one electrode, the probability that an identified trial belongs to the distribution is less than 1.6×10^{-12} . Assuming that all the true EEG activity values belong to a single gaussian distribution is unrealistic. Yet, given the large difference between the true EEG activity values and outliers, this approximation is not unreasonable in this context.

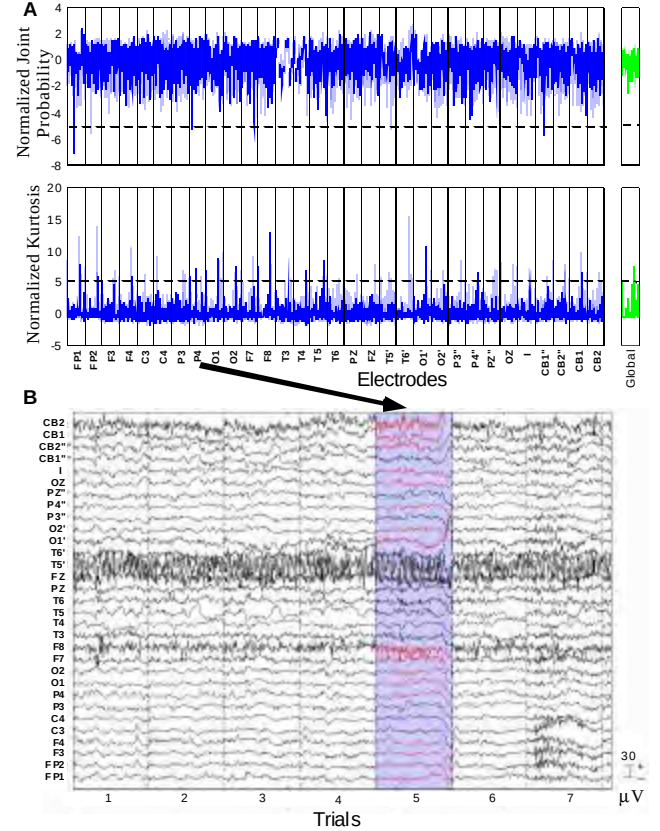


Figure 1. Rejection of artifact-laden trials on the statistics of single electrode activity in the raw data. A. Probability and kurtosis of the observed activity at each electrode for each trial. The horizontal dashed bars indicate rejection thresholds (in numbers of standard deviations from the mean). If the measure for one trial exceed one of these rejection thresholds, the trial is marked for rejection. B. Visualization of data at each electrode with suggested epoch labeled for rejection (the arrow indicates one of the electrodes for which the statistical measure on the labeled trial exceeds the threshold). Before accepting the suggested rejection, the user can review these plots. Rejected trials are depicted with a colored background and rejected components, with a specific color (not shown).

3. INDEPENDENT COMPONENT ANALYSIS AND EEG

3.1 Why use ICA

Having estimated these higher statistical properties of the signal, one might ask, why should we go further? All the measures we have used so far are based on raw potential values at single electrodes. However, EEG activity at different electrodes is highly correlated and thus contains redundant information. Also, several artifacts might be represented at the same set of electrodes and it would be useful if we could isolate and measure these artifacts based on their projection to overlapping electrode subsets. This is what ICA does [1][5]. Intuitively, one can imagine an n -electrode recording array as an n -dimensional space. The recorded signals can be projected into a more relevant coordinate frame than the single-electrode space: the independent component space. In this new coordinate frame, the projections of the data on each basis vector – i.e. the independent components – are maximally independent of each other. Assessing the statistical properties of the data reprojected onto these axes, we might be able to isolate and remove the artifacts more easily and efficiently.

ICA has been shown to be more efficient for this purpose than other algorithms such as principal component analysis (PCA) [2][3]. There are several reasons to use ICA. First, several major assumptions of using ICA seem to be fulfilled in the case of EEG recordings (for a detailed justification, see [1][6]). The first assumption is that the ICA component projections sum linearly onto the electrodes. This is actually the case for EEG in which different electrical sources – individual muscle and brain activations – sum linearly at scalp electrodes following Ohm's law. The second hypothesis is that sources are independent. This is not strictly realistic but even if artifact might be related to cognitive activation – a muscle contraction for instance is usually triggered by activity in the motor cortex – the time course of the artifact and the triggering event may be different in some or all trials. Thus, they will be accounted by different independent components [2]. A third assumption concerns the gaussianity of the sources: the source activity – i.e. the projection of the data onto the ICA basis vector – must not have a gaussian distribution. This last condition is quite plausible for artifacts, which are usually sparsely active and thus far from gaussian.

From the original data U , ICA finds a new projection space. Multiplication of U by the unmixing matrix W – found for example by infomax ICA [5] – represents a linear change of coordinate system, from the electrode space to the independent component space:

$$S = W * U \quad (4)$$

where S is the matrix of activations of the components across time in the new ICA coordinate frame (as shown in figure 3C). In EEG, each component is a linear weighted sum of the activity waveform at all the electrodes (the weights being a row of W). The independent components comprise these activations and the associated scalp maps give the projection weights of the components back into the electrode space. It is possible to derive the component spatial maps, as illustrated in figure 3A, as the columns of W^{-1} . For computing and visualizing ICA components, the software we developed uses the ICA Matlab toolbox for EEG of Makeig et al. (www.salk.edu/~scott/ica.html).

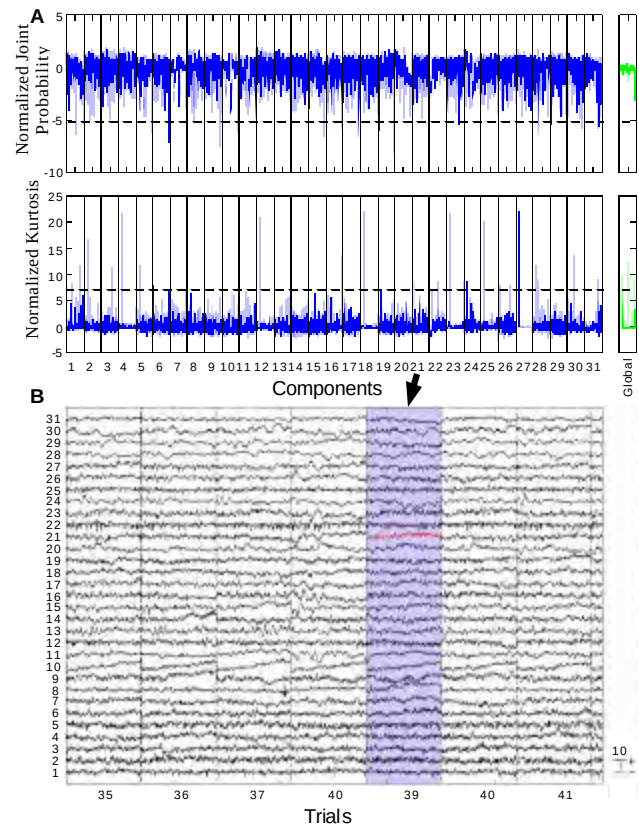


Figure 2. Detection of an artifact-laden trial based on the statistics of spatial independent components of 31-channel EEG. A. Probability and kurtosis of each component's activity in each trial. The horizontal dashed bars indicate rejection thresholds (in numbers of standard deviations from the mean). If the measure at one trial exceeds these rejection thresholds, the trial is marked for rejection. B. Activation of each component with trials marked for rejection (the arrow indicates which component was used to mark the labeled trial for rejection). Before accepting the rejection, the user can review these plots. Rejected trials are depicted with a colored background and rejected components, with a specific color (not shown).

3.2 ICA statistics and trial's rejection

Having computed the independent components of the data, we can try to detect outlier trials. As with raw data, we can compute both the probability and kurtosis of each trial for each component (see equations 1,2 and 3 above). As already point out, these measures can help us detect unexpected activity (using probability) or activity with an unusually peaky distribution (using kurtosis).

For rejecting single trials, we used either the joint probability or kurtosis of data in all components. As with the electrode data, we normalized the values of probability and kurtosis and then selected rejection thresholds in terms of number of standard deviation from the mean (figure 2). To refine the rejection criteria, we also defined a maximum number of components for which each measure should not exceed the rejection threshold. For instance if the maximum was set to 3 components and the data trial exceeded the rejection threshold at 4 components or more, then the trial was marked for rejection. The basic idea is that if the measure exceeds the rejection threshold at many components – i.e. the trial an outlier many components – then it is very likely to be an outlier trial in the original data. One might imagine that an artifact trial would only be expressed in a single independent component. The reality is more complex for various types of unpredictable noise (i.e. from coughing and other head movements), and several components are affected. Another example might be activity that saturates at some recording sites, thus altering the recording of other electrical sources from true EEG. As a consequence, the spatial and temporal structure of several components, found by preliminary ICA on the raw data, might be biased.

3.3 Component rejection and user calibration

While it is possible to reject artifact trials from component activity, it is also possible to subtract whole artifactual components from the original data. Instead of removing all the trials with muscle artifact activity for example, ICA decomposition allows the experimenter to subtract from the data the activity belonging to the artifactual muscle component. One can manually and visually rejects components based upon their spatiotemporal characteristics (figure 3), but one can also set a rejection threshold for relevant higher order statistics. We used three high-order statistical measures for each component: the entropy of the activity of the component (over all trials), the kurtosis of the activity and the kurtosis of the components' spatial map. Entropy for component i is defined as

$$H(i) = - \sum_{x \in D_i} p_{D_i}(x) \log(p_{D_i}(x)) \quad (5)$$

where $p_{D_i}(x)$ is the probability of observing the activity values x in the observed probability distribution of activity D_i from

component i . The use of the term entropy might be abusive because the measure computed in equation 5 is only a rough approximation of the true entropy of a component. The component activity values are not independent across time and trials but, because the distribution of activity of outlier components is very different from the standard distribution, this measure should be able to detect these outlier components. Additional terms could be added to equation 5 for minimizing the dependence of the entropy measure on the time step increment [7]. As a second measure, we used the kurtosis of the component's activity to detect sparse and peaky activity

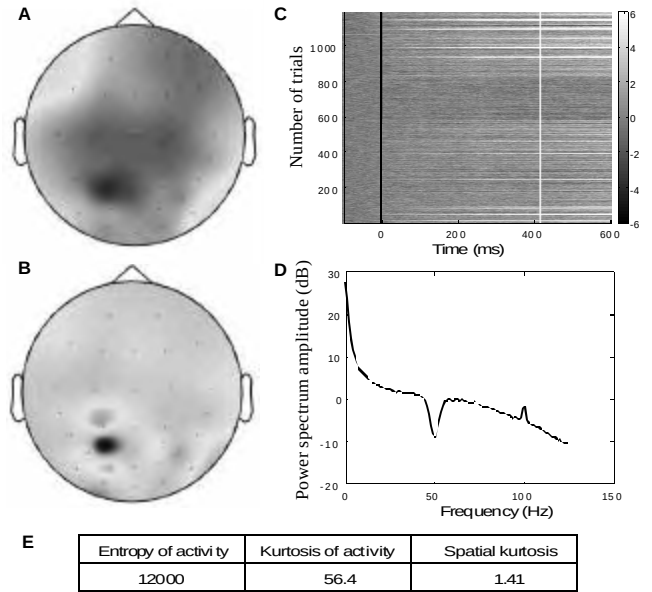


Figure 3. Characteristics of a non-muscle artifact component. A. Plot of the spatial map of the independent EEG component. B plot of the laplacian of the spatial map of the component. The laplacian helps to determine which electrodes are the most active in the component. If only one electrode is active (as it is approximately the case here), the component is likely to be an artifact. C. Plot of the component activity in 1200 single trials. Each single line is a different trial as in the ERP-image plotting format [6]. The color scale limits is arbitrary as ICA cannot retrieve the absolute amplitude of source activity. If the component is only active in a few trials, if it is not related the timing of the stimulus, or if it contains very high frequencies (>100Hz), it is very likely to be an artifact. D. The power spectrum of the component activity showing which frequencies dominate the component activity. If the component contain a homogenous distribution of high frequencies, it is likely to be an artifact component (note the notch filter at 50 Hz to remove noise from electrical lines). E. the three high-order statistical characteristics of this component (see text for details).

distribution, which are characteristic of some artifactual components (see equation 2 and 3). The last measure we used was the kurtosis of the spatial projection of the component. If the spatial projection of an artifactual component is peaky – for instance only one electrode is activated – then its kurtosis will have a high value. We will then be able to automatically detect and reject such components by setting an adequate rejection threshold.

Besides these three measures, the EEG-LAB user is presented with 4 graphical representations of the component: its spatial map, the laplacian of its spatial map, its individual trial activity and its frequency content. These representations provide the user with several types of information on which he can base his judgment for rejecting components (figure 3). Some spatial distributions for instance are typical for eye or muscle movements. They usually involve a single electrical polarity (positive or negative) and extend towards the edge of the skull (not shown).

To assess the efficiency of the three component statistics, we considered four classes of artifact components – eye blinks, eye movements, muscle activity and other types of artifacts. We visually rejected the components for four subjects performing a visual go-nogo categorization task of natural images (see the introduction for details on the experiment). This manual rejection was based upon the visual component characteristics as shown in figure 3. We then computed the probability that a component was rejected by this method as a function of the three statistical measure values. Figure 4 shows that all three measure values are correlated with selection as artifact and so can be used to detect artifacts. We observed that highest values of these measures seem to be characteristic of muscle components whereas intermediate values may be characteristic of non-muscle artifacts, and low values of non-artifact components. For eye blinks and eye movements, we only had two components per subject and we were not able to compute any statistics. However, the measures we computed might also be used to reject these components (for eye blink components: activity entropy 13400 ± 3200 , activity kurtosis 86 ± 68 and spatial kurtosis 4.8 ± 1.5 ; for eye movements: activity entropy 8580 ± 4900 , activity kurtosis 82 ± 55 and spatial kurtosis 9.8 ± 4.9). Though these results are still preliminary, they show that there is a relation between the statistics of the components and their rejection by at least one human experimenter. In the software we developed, the user can define thresholds for these three measures. Another screen shows the scalp maps of all the components, those marked for rejection by the program colored red. Buttons allow the user to review each component and to add and subtract from the rejection list. The final list chosen might be saved and used to calibrate subsequent processing.

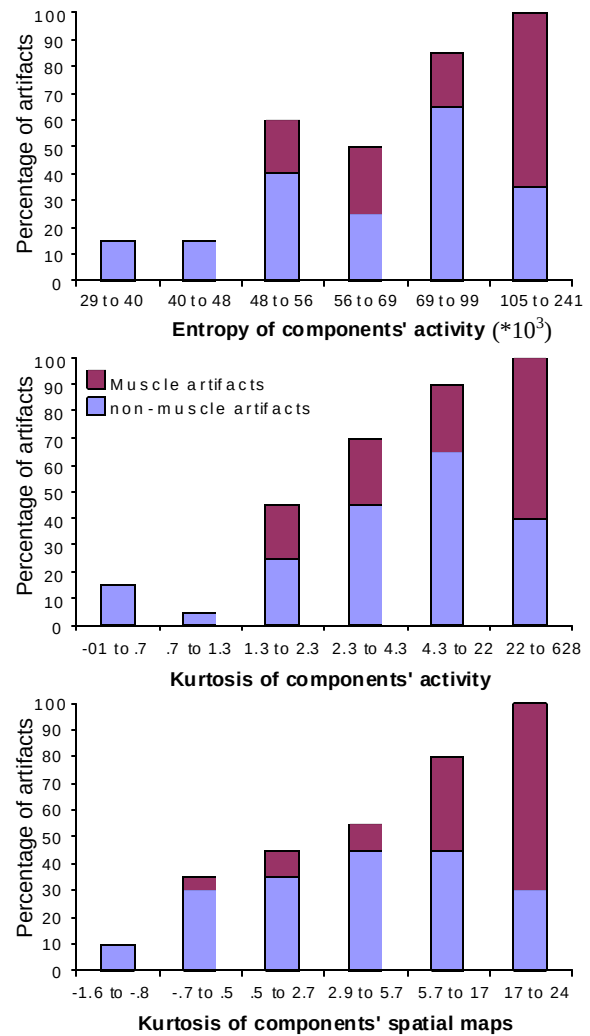


Figure 4. Component entropy and kurtosis as a function of experimenter rejections based on visual inspection of plots like figure 3 (4 subjects, 120 components out of which 65 were labeled as artifacts on visual inspection by the experimenter, A.D.). For each measure, we assessed the probability of the experimenter rejections. To compute the probabilities, we sorted the components by their entropy or kurtosis values and then partitioned the components into 6 consecutive groups of 20 (if 10 components in one of the groups are artifacts, then the artifact probability is 0.5). We considered 2 subconditions: muscle components (26), non-muscle components (39). We can see that the measures were quite accurate for detecting artifact. Extreme positive values of any of the measures corresponded to 100% of artifact components.

4. SUMMARY

As shown in figure 5, the EEG-LAB software we developed allows the user to combine and compare all types of rejection. We showed that using high-order statistics of the raw data and of the independent components, we may be able to semi-automatically reject trial artifacts. We also showed that high-order statistics of independent component activity are strongly correlated with the artifact/non-artifact distinction at least as defined by common practice in our laboratory. After artifact rejection, the cleaned data can be decomposed by ICA and/or other analysis method to study true EEG activity.

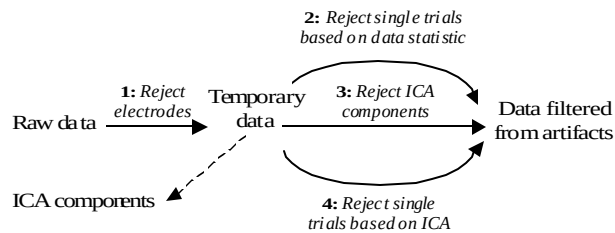


Figure 5. Schema for combining different types of rejection. After rejecting bad electrodes (1) and computing ICA, the algorithm combines three types of rejection. Trials can be rejected depending on the data statistics or the independent component statistics (respectively 2 and 4). Subtraction of artifactual independent components can also be performed (3).

We believe that one may detect artifacts more accurately using high-order statistical measures of the signals, regardless of the exact implementation of these measures. This approach allows experimenters to use information in the data that was taken into account by standard rejection methods. The graphical software we developed is open-source (software available at www.salk.edu/~arno/eeglab.html), with full documented source's code, and is organized hierarchically, meaning that complex graphical functions call simpler functions. It is thus easy to add new features. It also allows the user to directly call artifact rejection commands from a Matlab batch file and to combine these functions with other Matlab commands.

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Analysis of nonstationarity in renal autoregulation mechanisms using time-varying transfer and coherence functions

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Departments of ¹Biomedical Engineering and ²Physiology and Biophysics, State University of New York at Stony Brook, Stony Brook, New York; ³Department of Biology, University of Victoria, Victoria, BC, Canada; and ⁴Department of Biomedical Sciences, University of Copenhagen, Copenhagen, Denmark

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Chon KH, Zhong Y, Moore LC, Holstein-Rathlou NH, Cupples WA. Analysis of nonstationarity in renal autoregulation mechanisms using time-varying transfer and coherence functions. *Am J Physiol Regul Integr Comp Physiol* 295: R821–R828, 2008. First published May 21, 2008; doi:10.1152/ajpregu.00582.2007.—The extent to which renal blood flow dynamics vary in time and whether such variation contributes substantively to dynamic complexity have emerged as important questions. Data from Sprague-Dawley rats (SDR) and spontaneously hypertensive rats (SHR) were analyzed by time-varying transfer functions (TVTF) and time-varying coherence functions (TVCF). Both TVTF and TVCF allow quantification of nonstationarity in the frequency ranges associated with the autoregulatory mechanisms. TVTF analysis shows that autoregulatory gain in SDR and SHR varies in time and that SHR exhibit significantly more nonstationarity than SDR. TVTF gain in the frequency range associated with the myogenic mechanism was significantly higher in SDR than in SHR, but no statistical difference was found with tubuloglomerular (TGF) gain. Furthermore, TVCF analysis revealed that the coherence in both strains is significantly nonstationary and that low-frequency coherence was negatively correlated with autoregulatory gain. TVCF in the frequency range from 0.1 to 0.3 Hz was significantly higher in SDR (7 out of 7, >0.5) than in SHR (5 out of 6, <0.5), and consistent for all time points. For TGF frequency range (0.03–0.05 Hz), coherence exhibited substantial nonstationarity in both strains. Five of six SHR had mean coherence (<0.5), while four of seven SDR exhibited coherence (<0.5). Together, these results demonstrate substantial nonstationarity in autoregulatory dynamics in both SHR and SDR. Furthermore, they indicate that the nonstationarity accounts for most of the dynamic complexity in SDR, but that it accounts for only a part of the dynamic complexity in SHR.

hemodynamics; myogenic; tubuloglomerular feedback; hypertension

AUTOREGULATION OF RENAL BLOOD flow is mediated by the myogenic responses of the preglomerular vasculature (MYO) and the TGF feedback system. These two mechanisms exhibit characteristic resonant frequencies (MYO, 0.1–0.3 Hz; TGF, 0.02–0.05 Hz in rats). The marked difference in characteristic frequencies (and, hence, in time constants) between the TGF and MYO mechanisms permit separation and quantification of contributions of the two mechanisms by transfer function (1, 4, 29) and coherence analyses (2, 12).

A transfer function is the input-output relationship between an independent variable (blood pressure) and a dependent variable [renal blood flow (RBF)]. Its output is given in terms of gain, which reports fluctuation of the output with respect to the input and phase that contains the temporal relationship

between the two signals. Thus, normalized gain <0 dB indicates that RBF is stabilized with respect to blood pressure and hence that autoregulation is effective. The coherence function assesses the degree to which the data are related and provides information about the confidence one may have in the transfer function analysis. A high coherence at any frequency indicates that the input and output signals are closely and linearly related; reduced coherence can indicate the presence of noise, unrelated signals, or increased dynamic complexity.

Heretofore, all transfer function and correlation analyses of renal autoregulation have relied on the calculation of time-invariant linear transfer functions (TITF) and time-invariant linear coherence functions (TICF). These traditional methods assume that the system is linear, and that its dynamic characteristics do not vary with time (e.g., the system is stationary). Although both assumptions are questionable in the context of renal autoregulation, TITF and TICF analyses have proven to be useful tools in the study of renal hemodynamics (reviewed in Ref. 9). For example, a recent study using these time-invariant methods has reported conclusive evidence of differences in transfer function gains and coherence values between Sprague-Dawley rats (SDR) and spontaneously hypertensive rats (SHR), as well as rats with congestive heart failure, both with and without renal sympathetic denervation (13). This study also showed significantly increased coherence following renal denervation (13).

However, TICF typically reports low coherence at frequencies <0.05 Hz, in the region of the spectrum where TGF is operative, and often in the band from 0.1 to 0.2 Hz where the myogenic mechanism operates (e.g., see Ref. 16). Such a low coherence is generally held to severely limit the confidence one can place in the transfer function analysis. The low coherence has been attributed to the presence of significant nonlinearities in the autoregulatory mechanisms, because high coherence is routinely reported at higher frequencies. Previous studies examining nonlinear behavior of RBF dynamics used time-invariant analytical techniques so any time-varying behavior would have been interpreted as nonlinearities. Time-frequency mapping of the pressure and RBF (11, 33), as well as visual examination of many experimental records, suggests that time-varying behavior contributes substantially to dynamic complexity.

We have recently developed methods to compute time-varying transfer functions (TVTF) and time-varying coherence functions (TVCF) that are accurate and provide high frequency

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and time resolution (31, 32). In this investigation, we used these methods to analyze whole kidney blood flow data collected from SDR and SHR. Our goal is to test the hypotheses that 1) there is biologically significant nonstationarity in RBF dynamics of normotensive and hypertensive rats, 2) this nonstationarity accounts for some of the insensitivity of TITF analysis to known modulators of autoregulation, and 3) the greater dynamic complexity of RBF dynamics in SHR results at least in part from increased nonstationarity.

METHODS

Experimental procedures. Records of RBF and arterial pressure from seven SDR and six SHR were analyzed. In these records, an exogenous forcing of blood pressure was imposed to increase the power bandwidth to permit calculation of reliable transfer functions. The data were collected for a previously published study in which they were analyzed with time-invariant methods and where details of the experimental protocols are presented (3, 17). We have used the previously published data because one of our aims was to provide a direct comparison of the time-varying approaches to the TITF and TICF estimates since the latter calculations were based on the same data used in this work. These data have been used to assess how effectively a variety of techniques are to extract mechanistic insight from pressure-flow time series (5, 24, 27, 33). Here, the methods will be briefly summarized.

Animal preparation. The study was approved by the Animal Care Committees of the University of Southern California, and was conducted under the guidelines concerning the use of animals in research and teaching and the United States Public Health Service National Institutes of Health Guide for the Care and Use of Laboratory Animals. Experiments were performed on male SDR and SHR, 14–18 wk age and 250–300 g body wt. The rats had free access to food and water before the experiments. Anesthesia was induced by placing each rat in a chamber containing 5% halothane administered in 25% O₂-75% N through a Fluotec Mark-3 vaporizer. A tracheostomy was performed, and a small animal respirator was adjusted to maintain arterial blood pH between 7.35 and 7.45 with a mixture of 25% O₂-75% N. The final concentration of halothane needed to maintain sufficient anesthesia was ~1%. A polyethylene catheter was placed in the right jugular vein for infusions. After a priming dose of 6 mg gallamine triethiodide (Flaxedil) in 1 ml 0.9% saline, a continuous intravenous infusion of 60-mg gallamine triethiodide in 10 ml 0.9% saline was given at 20 μ l/min. Body temperature was maintained at 37°C by a servocontrolled heating table. The left kidney was exposed through a flank incision, immobilized with a lucite ring, and superfused with saline preheated at 37°C. Data acquisition started after a recovery period of 45 min.

Forcing of the arterial blood pressure and whole kidney pressure and blood flow measurement. Measurements of RBF and arterial pressure were made while broad-band fluctuations were induced in the distal aorta. A catheter was inserted into the superior mesenteric artery for measurement of the renal perfusion pressure since broad-band pressure fluctuations were induced in the distal aorta. The pressure in the superior mesenteric artery represents a kidney-filtered version of the broad-band pressure induced in the distal aorta. The left kidney was denervated and fitted with an electromagnetic flow probe. The aorta below the renal arteries was cannulated with a blood-filled catheter connected to a bellows pump, which in turn was driven by a computer-controlled motor. The blood was obtained from a donor rat on the day of the experiment. The input to the bellows pump was derived from a constant-switching-pace symmetric random input applied at 2 Hz and exhibited the spectral properties of band-limited white noise. Similar blood pressure power spectra were achieved in the SDR and SHR.

Data analysis. The arterial pressure and blood flow data were recorded on magnetic tape and digitized off-line. At that time, the signals were passed through a second-order low-pass Butterworth filter with cutoff at 1.5 Hz. The sampling rate for the blood pressure and flow measurements was ~9 Hz. Data were then preprocessed by low-pass filtering to 0.5 Hz and resampling to 1 Hz. Finally, each 1,024-point time series was subjected to low-order trend removal and normalized to zero mean and unit variance.

Statistical analysis was performed with a Student's *t*-test for unpaired data ($n = 7$ for SDR and $n = 6$ for SHR). To examine the time-varying nature of RBF dynamics, individual frequency vectors were extracted from the TVTF and TVCF and the means and standard deviations of these vectors were compared statistically. $P < 0.05$ was considered statistically significant. All data are presented as means $\pm$ SE.

TVTF and TVCF. Estimation of TVTF is based on a model-based approach known as the time-varying autoregressive moving average (TVARMA) model that has been reported in detail elsewhere (32). Similarly, details of the TVCF algorithm are reported elsewhere (31). However, we provide details of both TVTF and TVCF algorithms in APPENDIX A for the convenience of the readers. The TVTF and TVCF can be estimated via Eq. A6 and Eq. A7, respectively. The inverse Fourier transform of Eq. A6 represents the time-domain counterpart of the TVTF, and it is defined as the time-varying impulse response function. For example, a step response of the system can be obtained by integration of the impulse response function.

RESULTS

Application of TVTF. Representative TVTFs of SDR and SHR are shown in Figs. 1 and 2, respectively, as both magnitude and contour plots. For both SDR and SHR, the characteristic resonance peak is seen at ~0.2 Hz (5, 17). In both strains, gain magnitude declines sharply with decreasing frequency, indicating efficient autoregulation of RBF. Very low frequency fluctuations of TVTF gain magnitude are evident in both strains, and these fluctuations give the appearance of being periodic with a period of ~200 to 300 s. In contrast, SHR exhibit much greater temporal variation in gain magnitude at frequencies above ~0.02 Hz. Figure 3 illustrates the time-varying impulse response functions for these two rats. A time-varying impulse response function is the time domain counterpart of the TVTF, and it is the predicted response to a large, brief pulse in blood pressure. In both rats, predicted blood flow shows a rapid rise and fall with a marked undershoot and damped oscillations, whose period is consistent with the myogenic mechanism, during the relaxation to baseline. Note that the predicted impulse response is more stable over time in the SDR compared with the SHR, another indication that autoregulation in SD rats is more stationary than in SHR.

Quantification of nonstationarity. To quantify nonstationarity between the two strains of rats, we tracked the peak amplitude within the myogenic (0.1–0.3 Hz) frequency ranges for each time point. For TGF, tracking of the peak amplitude was not done since there was no obvious resonance peak associated with it. The method is illustrated in Fig. 4, *left*, which shows peak amplitude variations as a function of time for all SDR (black line) and SHR (gray line). The peak amplitude variations are greater for SHR than SDR. Fig. 4, *middle* and *right*, show minimum amplitude variations in the frequency range associated with the myogenic and TGF, respectively, for both SDR (black line) and SHR (gray line). Physically, they represent efficiency of autoregulation attributable to the myogenic and TGF mechanisms, respectively. In

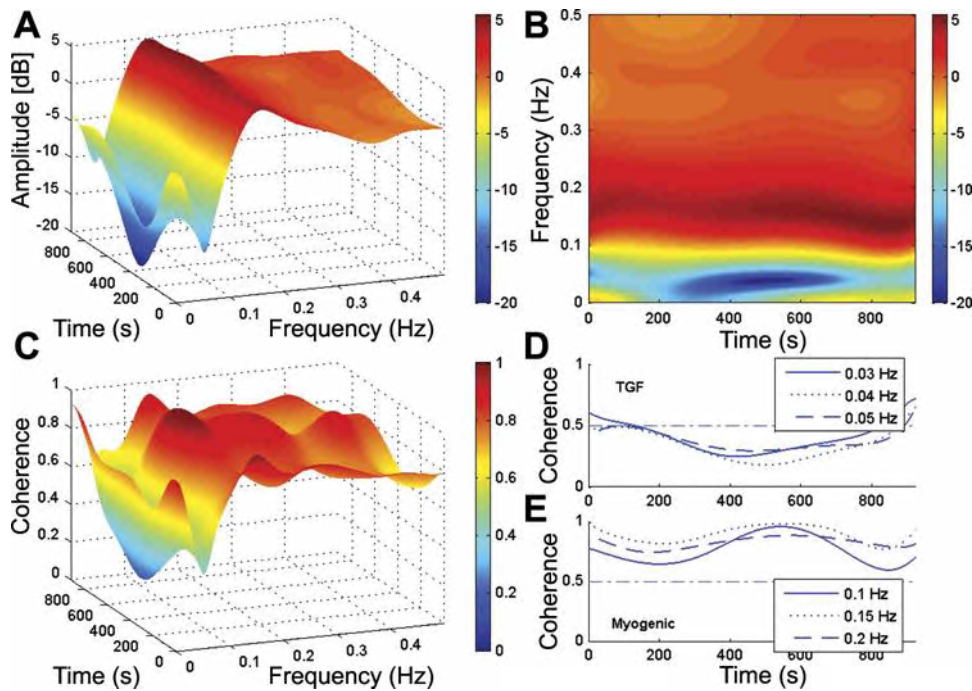


Fig. 1. Time-varying transfer functions (TVTF) of Sprague-Dawley rats (SDR; A: magnitude map, B: contour map), time-varying coherence function (TVCF; C), and time-varying coherence at 3 difference frequencies in tubuloglomerular (TGF) and myogenic frequency ranges (D and E), respectively.

both of these gain minimum plots, the average values were similar for SHR and SDR. However, variations are greater with SHR than SDR even though the power of the forced blood pressure fluctuations were comparable between SDR and SHR. Figure 5 shows quantitative analyses of plots shown in Fig. 4. There were significantly greater myogenic resonance amplitude peaks but with smaller variations for SDR than SHR. The greater significant variations in minimum gain values are also seen for SHR than SDR for the two frequency ranges associated with myogenic (Fig. 5, *middle*) and TGF (Fig. 5, *right*).

Time-varying coherence function. The TVCF is important because it provides insight into the correlation over time between the input and output signals (blood pressure and RBF, respectively). With TICF analysis, low coherence values can arise from noise, nonlinearity, and nonstationarity; hence, low coherence may not necessarily imply low correlation between the two signals. However, with the TVCF, one of the possible causes of the low coherence values, nonstationarity, can be eliminated. The estimated magnitude squared TVCFs for the two representative SDR and SHR are shown in Figs. 1C and

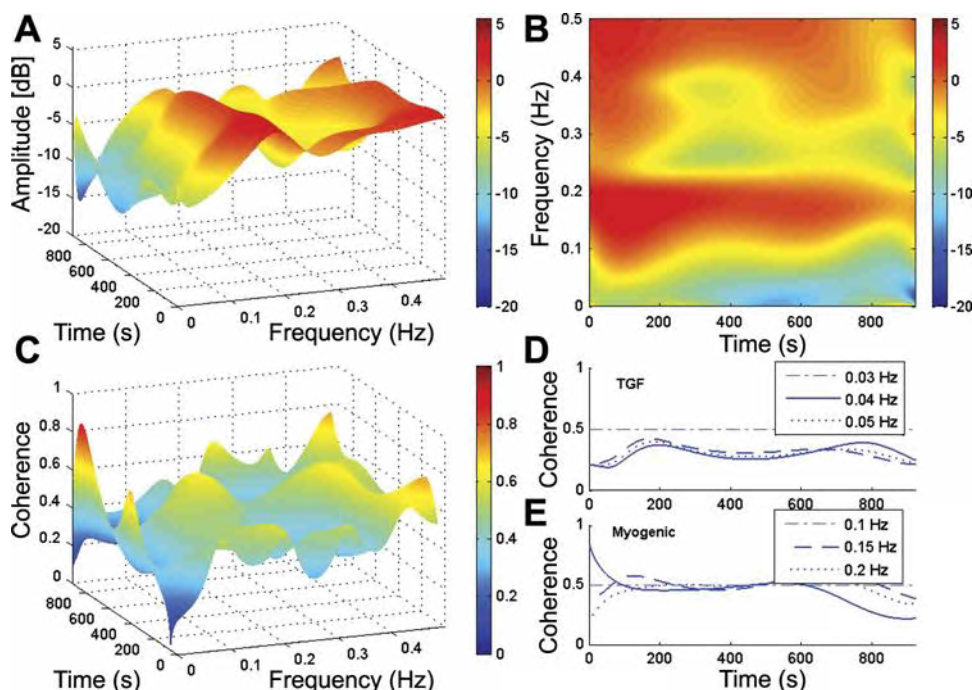
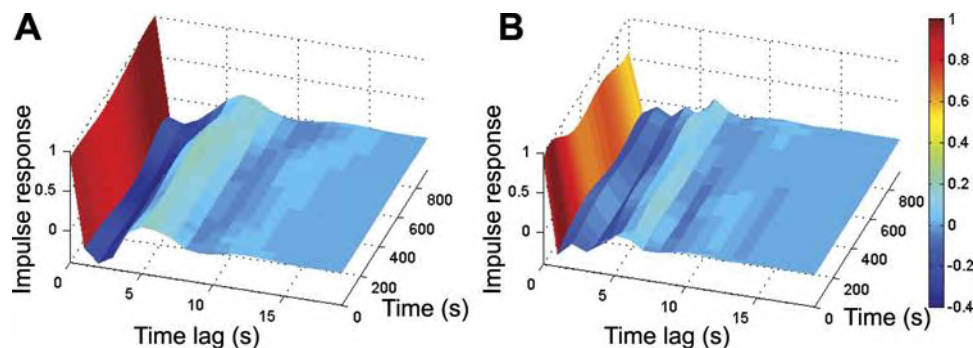


Fig. 2. TVTF of spontaneously hypertensive rats (SHR; A: magnitude map, B: contour map) and TVCF (C) and TVCF at 3 difference frequencies in TGF and myogenic frequency ranges (D and E), respectively.

Fig. 3. Time-varying impulse response functions of SDR (A) and SHR (B).



2C, respectively. Note that these are the same animals subjected to TVTF analysis (Fig. 1 and 2), and recall that coherence >0.5 is generally considered to be sufficient to permit the assumption of system linearity. For SDR, the TVCF of the MYO are consistently >0.5 throughout the time and frequency duration except for frequencies below 0.05 Hz, a region where coherence is expected to be reduced by autoregulatory adjustments in RBF (thus giving a low signal-to-noise ratio). For SHR, the coherence values are highly variable, usually <0.5 , and have even smaller values at frequencies <0.05 Hz. Figs. 1D and 2D show frequency slices of the TVCF at 0.03, 0.04, and 0.05 Hz, the frequency range where the TGF mechanism is known to operate. Fig. 1E illustrates frequency slices of the TVCF with the myogenic frequency band at 0.1, 0.15, and 0.2 Hz. For the myogenic mechanism of SDR, high coherence values are observed for all times although they vary from a high value of 1 to a low value of 0.6. For the myogenic mechanism of SHR, TVCF values are lower than for SDR and fluctuate around 0.5. In both strains, coherence within the TGF frequency band is lower and more time-dependent than in the myogenic frequency band. TGF in the SDR starts at a high coherence value, but with time transitions to lower coherence values. The TGF band of SHR, while time varying, shows consistently low coherence values. It is important to note that in both strains the times at which coherence is low correspond to the times at which the TVTF analysis (Fig. 1) indicate the most effective regulation of RBF. Furthermore, the very slow periodic variation evident in TVTF gain magnitude is also apparent in the TVCF. Hence, although the overall lower coherence in this SHR suggests that its autoregulatory systems are more nonlinear than in the SDR, much of the temporal

variation in both strains appears to be related to the very low frequency fluctuations in autoregulatory gain.

As shown in Fig. 6A, coherence values for the myogenic mechanism are consistently >0.5 for the normotensive rats and usually <0.5 for SHR (5 of 6 rats). For TGF, four out of seven normotensive rats exhibited coherence values >0.5 while five out of six SHR exhibited coherence values <0.5 . Fig. 6B provides mean TVCF values (averaged across all times) in the frequency ranges associated with the myogenic and TGF mechanisms for rats in both groups. The mean TVCF values for the myogenic mechanism are significantly greater for normotensive than hypertensive rats, and while the same is true for TGF, this increase is statistically nonsignificant.

DISCUSSION

The present study is the first systematic investigation of the time-varying properties of the renal autoregulatory mechanisms. Using recently-developed TVTF and TVCF approaches (31, 32), we were able to critically examine the stationarity of the TGF and myogenic autoregulatory mechanisms, to assess the extent that nonstationarities contributes to autoregulatory effectiveness and dynamic complexity. Based on information from studies of nonlinear dynamics (4, 6, 7, 21, 24, 28, 30) and from time-frequency mapping (11, 33), we predicted greater time-varying content in SHR than in SDR rats. The main findings of this study are that autoregulatory dynamics in both strains show significant variation over time, in the form of intermittent peaks and slow oscillations in transfer function gain. Furthermore, SHR exhibit significantly more temporal variability than SDR. Finally, compared with SDR, the major-

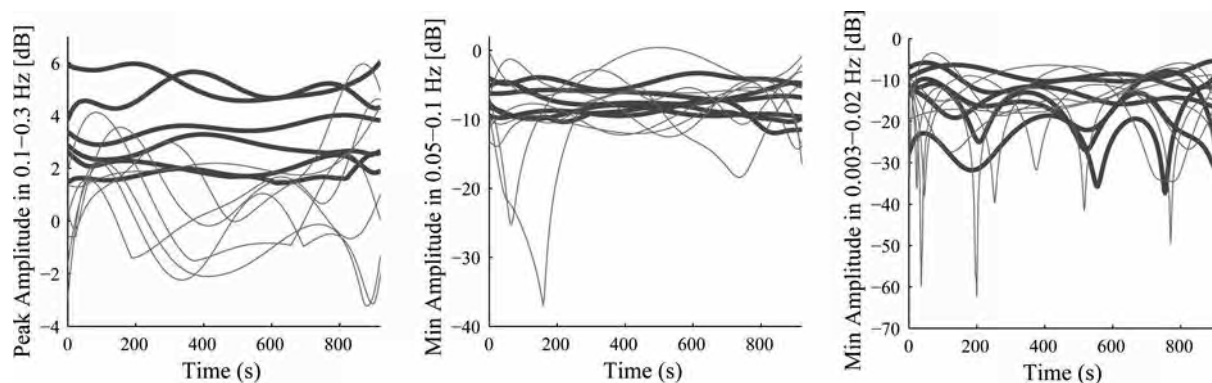


Fig. 4. Comparison of peak amplitudes of TVTF between SDR and SHR at the frequency range associated with the myogenic mechanism (left). Middle and right: variations of minimum TVTF amplitudes in the frequency ranges associated with the myogenic and TGF mechanisms, respectively.

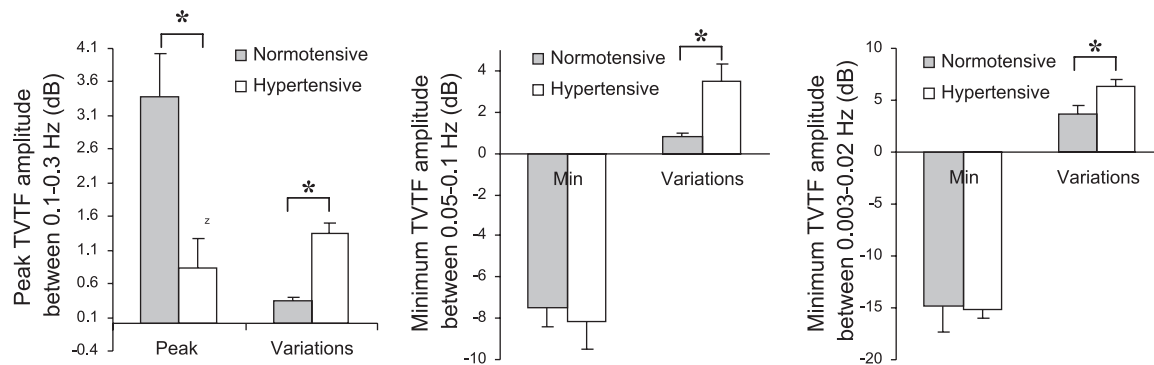


Fig. 5. Statistical comparison of peak amplitudes of TVTF between SDR and SHR at the frequency range associated with the myogenic mechanism (left). Middle and right: statistical comparison of minimum TVTF amplitudes between SDR and SHR in the frequency ranges associated with the myogenic and TGF mechanisms, respectively. * $P < 0.05$.

ity of SHR exhibit low time-varying coherence values in the frequency range associated with the myogenic and TGF mechanisms, including intervals in which gain is relatively stable, which suggests that the autoregulatory mechanisms in SHR are intrinsically more nonlinear than in normotensive SDR rats. The results of this study support and expand upon recent investigations of nonlinearity and nonstationarity in renal hemodynamics. Zou et al. (33) used various time-varying spectral techniques to demonstrate that both SDR and SHR exhibit time-varying renal autoregulatory responses, with greater nonstationarity observed in SHR. Cupples et al. (11) employed a different technique, Wigner-Ville spectra, to illustrate the time-varying properties of the renal autoregulatory mechanism in SDR.

The TVTF quantifies the gain relationship between RBF and arterial blood pressure at each instant in time and thus detects intermittent gain changes that occur. The TVTF approach used in this paper overcomes a fundamental limitation of short-time Fourier transform, a method widely used in time-varying spectral analysis. Using the short-time Fourier transform, a TVTF can be computed by division of time-varying cross spectrum (between blood flow and pressure) by the time-varying spectrum of a blood pressure signal. However, this approach leads to unreliable TVTF estimates in many cases, as the resolution in time and frequency vary inversely and is data length dependent. The result is that one cannot obtain simultaneous high time and frequency resolution (8). In contrast, our method provides excellent time and frequency resolution, provided that proper model coefficients [$a(k, n)$ and $b(k, n)$] in Eq. A1 have been determined. Determination of the proper

model coefficients of the TVTF utilized in this study has been previously demonstrated (32).

The observation that both the TGF and myogenic autoregulatory systems exhibit substantial time variability is not surprising given that these two mechanisms interact via a nonlinear feedback process to minimize blood flow variations despite forced blood pressure fluctuations (7, 14, 21, 24, 27). A prominent feature of the TVTF is the very low frequency modulation of gain magnitude in the TGF frequency range in both SDR and SHR, and in the myogenic frequency range in SHR. The origin of this phenomenon is unclear, but very low frequency oscillations in RBF have been noted in conscious dogs and attributed to fluctuations in ambient levels of vasoactive agents (28). Very low frequency oscillations in RBF have also been induced by blood pressure forcing (11), and may be related to the slow component of renal autoregulation suggested by Just and coworkers (18, 19). Furthermore, because of the known interactions between the TGF and myogenic mechanisms, the fact that both autoregulatory systems exhibited some degree of nonstationarity is to be expected. In the steady-state, both experimental and modeling studies have shown a strong dependence of the myogenic autoregulatory system on TGF, such that myogenic compensation is enhanced when the TGF system is stimulated (15, 23, 25). Similarly, both the myogenic mechanism (25) and TGF (31) are extensively modulated by ANG II, the generation of which is at least partly TGF dependent. Furthermore, there are nonlinear interactions between these two systems that produce spectral peaks (7, 21, 24) and changes in overall system behavior (19, 20). In addition, the state of the TGF system appears to modulate the

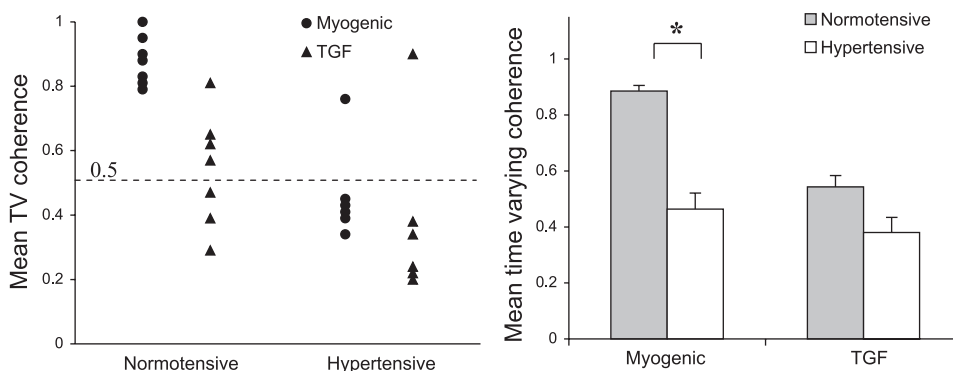


Fig. 6. Distribution of mean time-varying coherence values in the myogenic and TGF frequency ranges for SDR and SHR, respectively (A); Mean time-varying coherence values in the frequency ranges associated with the myogenic and TGF mechanisms for rats in both groups (B). * $P < 0.05$.

resonant frequency of the myogenic mechanism (26, 27). Hence, even if the strength of either of these two mechanisms is modulated over time by exogenous factors, it is to be expected that the state and responsiveness of the other mechanism will be affected.

It is important to recognize that information concerning this kind of time-varying behavior would be lost in a time-invariant transfer function, which would represent just the time average of features evident in a TVTF. As a result, the time-resolution of time-invariant methods is very limited, and any nonstationarity that is present may distort the spectra and introduce artifactual spectral complexity (21). Nevertheless, time-invariant methods have played an important role in elucidating the dynamics of renal autoregulation. Several laboratories (10, 12, 16) first used the TITF to demonstrate operative dynamics of renal autoregulation. The simple calculation of TITF based on the ratio of the spectra of the blood pressure and flow, and insights it provided, led other investigators to look for differences in transfer function gain between SDR and SHR (5), before and after administration of pharmacological agents (11), between healthy rats and rats with renal disease (2, 20), and before and after renal denervation in several species (13). In the aforementioned studies, statistically significant differences were not always found using TITF, although in each case there was good reason to expect such differences, which suggests that the TITF method may be not be sensitive enough to detect significant changes in dynamics when the data are even modestly nonstationary. Thus, TVTF methods are preferable, and it would seem prudent to employ time-varying spectral methods to verify that negative conclusions are not a consequence of nonstationarity.

Analysis of coherence with time-invariant methods has been used to assess linearity of the autoregulatory mechanisms (5, 10, 13). Two of these studies have reported higher coherence values in the frequency ranges associated with the myogenic and TGF mechanisms for SDR than for SHR (10, 13). Furthermore, it has been shown that for both SDR and SHR, coherence values are generally >0.5 at frequencies faster than 0.1 Hz and are consistently lower at frequencies slower than 0.05 Hz. The low coherence values observed with the TGF mechanism for both SDR and SHR have been attributed to the nonlinear dynamics of TGF (6, 7), and, in some cases, coherence values were lower for SHR than for SDR (4, 13). A report by Yip and Holstein-Rathlou (30) has suggested that the lower coherence values in SHR may, in part, be due to chaotic behavior of TGF in this strain. Our results using the TVCF are generally consistent with these findings. In several frequency bands, we found coherence to exhibit more time-varying behavior and to be significantly lower in SHR than in SDR. Because the TVCF does not assume stationarity, the fact that we still observe low coherence values in SHR is consistent with the idea that the autoregulatory systems in SHR are more nonlinear than in normotensive rats.

Nevertheless, there are two notable differences between our study and previous investigations using TITF. First, high coherence values of the myogenic mechanism were consistently observed in both SHR and SDR in previous studies using TITF, whereas this was only true for SDR with TVCF analysis. Second, unlike previous studies, we observe high coherence values for the TGF mechanism in most SDR (4 out of 7). These observations suggest that autoregulatory mechanisms may ex-

hibit quasilinear control properties in SDR and nonlinear control properties in SHR. While further analyses are required on diverse sets of experimental data, the present results suggest that autoregulatory mechanisms in hypertension are dominated by nonlinear control processes. It is unclear as to what or why autoregulatory mechanisms exhibit nonlinear control properties in SHR, although two recent hypotheses may be relevant. In a simulation study, Ditlevsen et al. (14) proposed that the nonlinear dynamics exhibited by SHR can be explained by relatively large and rapid random fluctuations in TGF system gain, a parameter chosen "to represent mechanisms not explicitly included in the model" (14). Layton et al. (21) have suggested that a sufficient explanation for the irregular fluctuations in the TGF system in SHR may involve resetting and temporal variation in TGF gain and/or time delays in coupled nephrons that may result in abrupt switching between multiple stable oscillatory modes. It is interesting that both of these hypotheses involve parameter nonstationarity. Hence, the availability of high resolution time-varying methods for spectral and transfer function analysis will be of value in experimental investigations of these hypotheses.

In summary, nonstationarities in both the myogenic and TGR feedback mechanisms were observed in normotensive rats, while the nonstationary characteristics in hypertensive rats were significantly greater, as both mechanisms displayed very low frequency oscillations in gain and coherence. Furthermore, hypertensive rats appear to have lower time-varying admittance gain (and thus less variation in blood flow), especially in the myogenic frequency range and consistently lower TVCF values than normotensive rats. Our results indicate that although the autoregulatory dynamics of normotensive rats are often quasilinear, hypertensive rat dynamics are much more complicated and require analysis with methods designed to capture both nonlinear and time-varying system dynamics.

Perspectives and Significance

It has been apparent for some time that RBF autoregulation exhibits dynamics that are more complex than can be captured by linear, time-invariant analysis. To some extent this complexity arises out of the system's anatomy; both TGF and the myogenic mechanism operate on afferent arteriolar resistance, while the TGF sensor is downstream of all other components of the combined system. But it is also clear that the complexity of RBF dynamics is greater in hypertensive than in normotensive rats (3, 4). To a very large extent, previous studies addressing this complexity have lumped together nonlinear and nonstationary (time-varying) behavior and have not differentiated between the two. The present results show that autoregulatory efficiency shows substantial variation in time in both normotensive (SDR) and hypertensive (SHR) rats. In SDR the nonstationarity accounts for a large fraction of the previously observed dynamic complexity was not captured by TITF. In SHR, however, although the time-variance of autoregulation is even greater than that in SDR, there remains a substantial fraction of dynamic complexity that is not explained by time-variance. Clearly, future studies will need to address both mechanisms and implications of time-variance in autoregulatory efficiency.

APPENDIX A

Estimation of TVTF is based on a model-based approach known as the TVARMA model (32). While theoretically it is possible to calculate TVTF using the division of the time-varying cross spectrum by the time-varying auto spectrum, it is impractical because most time-varying spectra exhibit zero power, which precludes calculation of a TVTF.

The TVARMA process is represented by the following equation

$$y(n) = \sum_{i=1}^P a(i, n)y(n-i) + \sum_{j=0}^Q b(j, n)x(n-j) + e(n) \quad (A1)$$

where $a(i, n)$ and $b(j, n)$ are the TVARMA coefficients to be determined, respectively, and are functions of time. Indexes P and Q are the maximum model orders of the autoregressive and moving average models, respectively. Variables $y(n)$ (blood flow) and $x(n)$ (blood pressure) represent output and input signals, respectively. The term $e(n)$ is the prediction error. The time-varying coefficients $a(i, n)$ and $b(j, n)$ are expanded onto a set of basis functions $\pi_k(n)$

$$\begin{aligned} a(i, n) &= \sum_{k=0}^V \alpha(i, k)\pi_k(n) \\ b(j, n) &= \sum_{k=0}^V \beta(j, k)\pi_k(n) \end{aligned} \quad (A2)$$

where $\alpha(i, k)$ and $\beta(j, k)$ represent the expansion parameters with V as the maximum number of basis sequences. Substituting Eq. A2 into Eq. A1, we obtain the following

$$\begin{aligned} y(n) &= \sum_{i=1}^P \sum_{k=0}^V \alpha(i, k)\pi_k(n)x(n-i) \\ &+ \sum_{j=0}^Q \sum_{k=0}^V \beta(j, k)\pi_k(n)x(n-j) + e(n) \end{aligned} \quad (A3)$$

For data analyses, we have used Legendre polynomials as they are most appropriate for smoothly changing dynamics. APPENDIX B details the use of Legendre functions and provides information on how to choose the proper number of V in Eq. A3.

Once proper basis functions, $\pi_k(n)$, have been chosen (Legendre), we create new variables

$$\begin{aligned} y_k(n-i) &= \pi_k(n)y(n-i) \\ x_k(n-j) &= \pi_k(n)x(n-j) \end{aligned} \quad (A4)$$

Substituting Eq. A4 into Eq. A3 results in the following expression

$$y(n) = \sum_{i=1}^P \sum_{k=0}^V \alpha(i, k)y_k(n-i) + \sum_{j=0}^Q \sum_{k=0}^V \beta(j, k)x_k(n-j) + e(n) \quad (A5)$$

Equation A5 shows that the TVARMA model can now be considered to be a TIV-ARMA model since $\alpha(i, k)$ and $\beta(j, k)$ are not functions of time. Thus, the task simplifies to solving for parameters $\alpha(i, k)$ and $\beta(j, k)$, which can be more effectively estimated using the optimal parameter search algorithm (22). For details of the optimal parameter search algorithm concerning model order determination and the selection of only the significant model terms, the reader is referred to Lu et al. (22).

Once the time-varying ARMA coefficients are identified, the TVTF can be easily estimated using the following

$$H(n, e^{j\omega}) = \frac{\sum_{k_2=0}^Q b(k_2, n)e^{-j\omega k_2}}{\sum_{k_1=1}^P a(k_1, n)e^{-j\omega k_1}} \quad (A6)$$

The norm of $H(n, e^{j\omega})$, $\|H(n, e^{j\omega})\|$ represents the time-varying gain of the linear time-varying system, and the angle of $H(n, e^{j\omega})$, $\angle H(n, e^{j\omega})$ represents the time-varying phase of the linear time-varying system. $H(n, e^{j\omega})$ is an extension of the linear time-invariant system such that the single variable, either time or frequency, is mapped to the two variables of time and frequency.

TVCF. In this section, we demonstrate that the TVCF can be obtained by using the TVTF relationships (43). To demonstrate the use of the TVTF in obtaining the TVCF, we first define the TVCF via the nonparametric time-frequency spectra

$$|\gamma(t, f)|^4 = \left(\frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)} \right) \left(\frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)} \right) \quad (A7)$$

where $S_{xy}(t, f)$ and $S_{yx}(t, f)$ represent the time-frequency cross spectrum, and $S_{xx}(t, f)$ and $S_{yy}(t, f)$ denote the auto spectrum of the two signals x and y , respectively. The above expression $\frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)}$ is the coherence function when x is considered as the input and y as the output, while $\frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)}$ is the coherence function when y is considered as the input and x as the output. We note that for a linear time-varying system with x and y as the input and output signals, respectively, the following TVTF in terms of time-frequency spectra can be obtained

$$H_{xy}(t, f) = \frac{S_{xy}(t, f)}{S_{xx}(t, f)} \quad (A8)$$

where $H_{xy}(t, f)$ denotes the TVTF from the input x to the output y signals. Similarly, if we reversed the input and output relationship such that the variables y and x represent input and output signals, respectively, then the following TVTF can be obtained

$$H_{yx}(t, f) = \frac{S_{yx}(t, f)}{S_{yy}(t, f)} \quad (A9)$$

The desired relationship of Eq. A7 can be obtained by multiplying the two TVTF relationships of Eq. A8 and Eq. A9, which yields

$$\begin{aligned} |H_{xy}(t, f)H_{yx}(t, f)|^2 &= \left| \frac{S_{xy}(t, f)}{S_{xx}(t, f)S_{yy}(t, f)} \right|^2 \cdot \left| \frac{S_{yx}(t, f)}{S_{yy}(t, f)S_{xx}(t, f)} \right|^2 \\ &= \frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)} \cdot \frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)} = |\gamma(t, f)|^4 \end{aligned} \quad (A10)$$

Thus, time-varying magnitude squared coherence, $|\gamma(t, f)|^2$, is then obtained by multiplying the two transfer functions, $|H_{xy}(t, f)H_{yx}(t, f)|$, together.

Given the relationship of Eq. A10, a high resolution TVCF via the parametric TVTF can be obtained. Specifically, each of the two transfer functions in Eq. A10 can be obtained using autoregressive moving average models such that

$$y(n) = \sum_{i=1}^P a(n, i)y(n-i) + \sum_{j=0}^Q b(n, j)x(n-j) + e_1(t) \quad (A11)$$

$$x(n) = \sum_{i=1}^P \alpha(n, i)x(n-i) + \sum_{j=0}^Q \beta(n, j)y(n-j) + e_2(t)$$

where ARMA models of the top and bottom expressions in Eq. A11 represent $y(n)$ as the output and $x(n)$ as the output, respectively. Given the ARMA models of Eq. A11, the two transfer functions of Eq. A10 can be obtained by the following equation

$$H_{xy}(n, e^{j\omega}) = \frac{B(e^{j\omega})}{A(e^{j\omega})} = \frac{\sum_{j=0}^Q b(n, j)e^{-j\omega j}}{\sum_{i=0}^P a(n, i)e^{-j\omega i}} \quad (A12)$$

$$H_{yx}(n, e^{j\omega}) = \frac{\beta(e^{j\omega})}{\alpha(e^{j\omega})} = \frac{\sum_{j=0}^Q \beta(n, j)e^{-j\omega j}}{\sum_{i=0}^P \alpha(n, i)e^{-j\omega i}}$$

APPENDIX B

Legendre polynomials. Recurrence relations to generate Legendre polynomials are provided below

$$P_0(x) = 1$$

$$P_1(x) = x$$

$$(l+1)P_{l+1}(x) = (2l+1)xP_l(x) - lP_{l-1}(x)$$

We chose Legendre basis functions for their exponential characteristics, which make them especially suitable for modeling biological systems (31, 32). The number of coefficients estimated depends on the choice of TVARMA model orders P and Q as well as the selection of V in Eq. A3. Specifically, the total number of coefficients to be estimated is $P(V+1) + (Q+1)(V+1)$. Note that other time-varying approaches utilize far more parameters than does our approach (31, 32). The determination of the number of time-varying basis functions V requires some a priori knowledge of the nonstationarities in a system. We based our choice of the appropriate values of V on the mean square error (MSE) criterion. We have shown that the MSE values gradually decrease as the number of basis sequences increase, but when V is too large, the MSE value will become exorbitantly large. Thus, the approach to take to determine the sufficient number of V is to increase V until the MSE value no longer decreases.

GRANT

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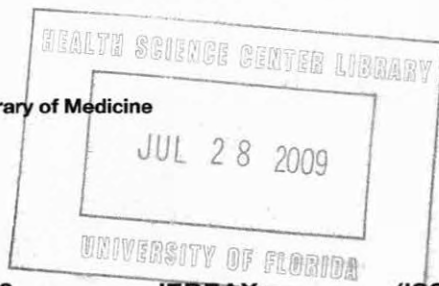
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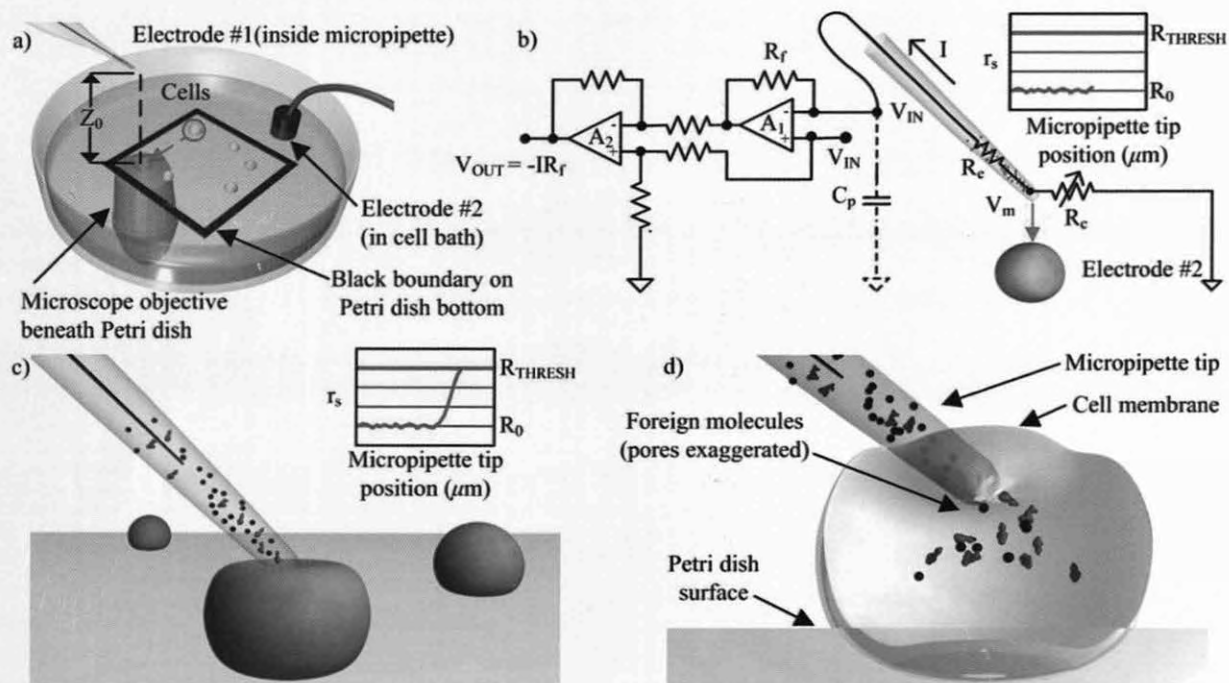
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Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation

Ki H. Chon*, Senior Member, IEEE, Shishir Dash, and Kihwan Ju

Abstract—We present a new method that uses the pulse oximeter signal to estimate the respiratory rate. The method uses a recently developed time–frequency spectral estimation method, variable-frequency complex demodulation (VFCDM), to identify frequency modulation (FM) of the photoplethysmogram waveform. This FM has a measurable periodicity, which provides an estimate of the respiration period. We compared the performance of VFCDM to the continuous wavelet transform (CWT) and autoregressive (AR) model approaches. The CWT method also utilizes the respiratory sinus arrhythmia effect as represented by either FM or AM to estimate respiratory rates. Both CWT and AR model methods have been previously shown to provide reasonably good estimates of breathing rates that are in the normal range (12–26 breaths/min). However, to our knowledge, breathing rates higher than 26 breaths/min and the real-time performance of these algorithms are yet to be tested. Our analysis based on 15 healthy subjects reveals that the VFCDM method provides the best results in terms of accuracy (smaller median error), consistency (smaller interquartile range of the median value), and computational efficiency (less than 0.3 s on 1 min of data using a MATLAB implementation) to extract breathing rates that varied from 12–36 breaths/min.

Index Terms—FM, pulse oximeter, respiratory sinus arrhythmia, time–frequency analysis.

I. INTRODUCTION

FOR patients at risk of cardiorespiratory failure, it is important to monitor the efficiency of gas exchange in the lungs, i.e., how well the arterial blood is oxygenated [1]. A noninvasive means to monitor arterial oxygen saturation (SaO_2) on a continuous basis is pulse oximetry, a well-established technology based on photoplethysmography (PPG) that has become one of the most commonly used patient monitors during anesthesia and in intensive care units. Its popularity stems from the fact that the pulse oximeter can be used to noninvasively measure both SaO_2 and basic cardiac function (e.g., heart rhythms). Furthermore, it is simple to operate and does not discomfort patients.

Given the ubiquity and simplicity of pulse oximetry, it is desirable to maximize its potential by exploring additional measure-

ments that we can derive from the pulse oximeter. Extraction of respiratory rate from pulse oximetry data is one example, as the signal from the pulse oximeter contains not only the heart beat but also a respiratory signal. Respiratory rate is important for many clinical uses including detecting sleep apnea [2], sudden infant death syndrome [3], and chronic obstructive pulmonary disease [4], and measurements of respiratory rate are indicated in many intensive care and operative settings. The current standard practice for the automatic measurement of respiration rate requires monitoring of CO_2 production using a capnograph, which is an expensive device that requires a significant amount of maintenance. In addition, it requires a mask or nasal cannula, and is therefore obtrusive to the patient and cumbersome to use. Obtaining accurate respiratory rates from a pulse oximeter in addition to SaO_2 and heart rate is very appealing from both economic and patient comfort perspectives.

The reason why many researchers feel that it is possible to obtain respiratory rate from the PPG signal is due to evidence that the respiration rate modulates both amplitude and frequency of the signal [5]–[8]. This phenomenon is similar to the respiratory sinus arrhythmia modulating the heart rate signal. Thus, this suggests that the respiratory rate can be obtained by detecting the presence of AM and FM. However, detection of these modulations is often difficult, due to myriad causes [9]–[11]. Three primary culprits stand out: 1) the time-varying (TV) nature of these modulations; 2) both AM and FM are often subtle, and thus, the highest possible time and frequency resolutions are needed to detect them; and 3) the presence of motion and noise artifacts can mask AM and FM.

To this end, many recent efforts using advanced signal processing algorithms to overcome the aforementioned problems have shown tantalizing potential. Using a series of adaptive low-pass filters (LPFs) followed by high-pass filters with suitable cutoff frequencies, Nakajima *et al.* [9] were able to show that heart and respiratory signals can be distinguished in the PPG signal. However, this technique's accuracy degrades with motion artifacts, which are especially prevalent in the PPG signal during exercise. Furthermore, the cutoff frequencies of the low- and high-pass filters need to be tailored to individuals, which preclude wide clinical use. With the recent introduction of new techniques using estimation of time–frequency spectra (TFS) for analyzing nonstationary signals, there is at last the promise of succeeding at our goal. In this category, several studies have utilized short-time Fourier transform (STFT) [8] and continuous wavelet transform (CWT) [5]–[7], [12]–[14] to extract the respiratory rate from the PPG signal. However, success is predicated

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on obtaining the highest possible time and frequency resolution, which is impossible with either the STFT or the CWT. It is widely known that the CWT cannot simultaneously provide high resolution in time and high resolution in frequency. Generally, CWTs provide high resolution in frequency only at low frequencies and high time resolution only at high frequencies. For subjects with chronic obstructive pulmonary disease, reflection of respiratory rate via the AM and FM of the PPG signal is often subtle as these subjects are physically limited from breathing in a normal manner. It is unclear what is considered “LF” because the LF range can vary depending on the dynamics of the system. Furthermore, real-time implementation is especially challenging for the CWT. The studies by Leonard *et al.* [5]–[7], Addison and Watson [12], [13], and Clifton *et al.* [14] show relatively good results; however, the CWT is impractical because the extraction of respiratory rate is done in some cases with the use of FM while in other cases with the AM of heart rate. This is clearly a difficult situation since it would require additional adaptive decision-making schemes to determine when to use either FM or AM of the heart rate signal to extract respiratory rates.

Recently, a method based on autoregressive (AR) modeling has been proposed, claiming to provide more accurate results than the existing techniques [15]. While the method is easy to implement, this approach is also problematic because the AR model order needs to be tuned to an individual, or at best, to specific age groups and/or for specific time periods studied. For example, the AR model requires different sets of modeling parameters for 5 min and 30 s data, respectively. Furthermore, a separate threshold criterion is needed to identify poles with the highest magnitude as there can be multiple poles meeting the specifications.

To improve upon the limitations of current techniques, the goal of this paper is the application of a new algorithm that we have recently developed [16], which is able to accurately extract continuous respiratory rate from noninvasive recordings of PPG signals. The algorithm is based on one of the highest possible time and frequency resolution approaches to estimating TFS and associated amplitudes via the use of variable-frequency complex demodulation (VFCDM) [16]. The VFCDM provides the best time and frequency resolution and most accurate amplitude estimates when compared to the smoothed pseudo-Wigner-Ville, CWT, and Hilbert–Huang transform methods [16]. Thus, it is expected that the VFCDM algorithm will be more accurate than the power spectral density, CWT, and other time–frequency-based methods for determining respiratory rate. Indeed, with this implementation, we are able to accurately extract wide ranges of respiratory rates from the raw PPG signals. The VFCDM method was tested on 15 different subjects for breathing frequencies ranging from 0.2 to 0.6 Hz. Results were compared to the CWT method [5]–[7], [12]–[14] and an AR model method [15], which have been shown to be among the best existing techniques for extracting breathing rate information from PPG signals.

II. METHODS

A. Algorithm Development

The VFCDM method has been published and tested with different physiological signals [16]–[18], and thus, will be briefly

summarized. For further details than what is provided in this section, see [16].

1) *VFCDMs for Estimation of TFS*: The VFCDM method involves a two-step procedure. The first step is to use the complex demodulation (CDM) or what we termed the fixed-frequency CDM (FFCDM) to obtain an estimate of the TFS, and the second step is to select only the dominant frequencies of interest for further refinement of the time–frequency resolution using the VFCDM approach. In the first step of the VFCDM method, a bank of LPFs is used to decompose the signal into a suite of band-limited signals. The analytic signals that are obtained from these, through use of the Hilbert transform, then provide estimates of instantaneous amplitude, frequency, and phase within each frequency band. Consider a sinusoidal signal $x(t)$ to be a narrow-band oscillation with a center frequency f_0 , instantaneous amplitude $A(t)$, phase $\phi(t)$, and the direct current component $dc(t)$ defined as

$$x(t) = dc(t) + A(t) \cos(2\pi f_0 t + \phi(t)). \quad (1)$$

For a given center frequency, we can extract the instantaneous amplitude information $A(t)$ and phase information $\phi(t)$ by multiplying (1) by $e^{-j2\pi f_0 t}$, which results in the following:

$$\begin{aligned} z(t) &= x(t)e^{-j2\pi f_0 t} \\ &= dc(t)e^{-j2\pi f_0 t} + \left(\frac{A(t)}{2}\right)e^{j\phi(t)} \\ &\quad + \left(\frac{A(t)}{2}\right)e^{-j(4\pi f_0 t + \phi(t))}. \end{aligned} \quad (2)$$

A leftward shift by $e^{-j2\pi f_0 t}$ moves the center frequency f_0 to zero frequency in the spectrum of $z(t)$. If $z(t)$ in (2) is subjected to an ideal LPF with a cutoff frequency $f_c < f_0$, then the filtered signal $z_{lp}(t)$ will contain only the component of interest, and we obtain the following:

$$z_{lp}(t) = \left(\frac{A(t)}{2}\right)e^{j\phi(t)} \quad (3)$$

$$A(t) = 2|z_{lp}(t)| \quad (4)$$

$$\phi(t) = \tan^{-1} \left(\frac{\text{Im}(z_{lp}(t))}{\text{Re}(z_{lp}(t))} \right). \quad (5)$$

Consider a case when a modulating frequency is not fixed as described before but varies as a function of time. In this case, the signal $x(t)$ can be written in the following form:

$$x(t) = dc(t) + A(t) \cos \left(\int_0^t 2\pi f(\tau) d\tau + \phi(t) \right). \quad (6)$$

Similar to the operations in (1) and (2), multiplying (6) by $e^{-j \int_0^t 2\pi f(\tau) d\tau}$ yields both instantaneous amplitude $A(t)$ and instantaneous phase $\phi(t)$, so that

$$\begin{aligned} z(t) &= x(t)e^{-j \int_0^t 2\pi f(\tau) d\tau} \\ &= dc(t)e^{-j \int_0^t 2\pi f(\tau) d\tau} + \left(\frac{A(t)}{2}\right)e^{j\phi(t)} \\ &\quad + \left(\frac{A(t)}{2}\right)e^{-j \left(\int_0^t 4\pi f(\tau) d\tau + \phi(t) \right)}. \end{aligned} \quad (7)$$

From (7), if $z(t)$ is filtered with an ideal LPF with a cutoff frequency $f_c < f_0$, then the filtered signal $z_{lp}(t)$ will be obtained with the same instantaneous amplitude $A(t)$ and phase $\phi(t)$ as provided in (4) and (5). The instantaneous frequency is given by [19] as

$$f(t) = f_0 + \frac{1}{2\pi} \frac{d\phi(t)}{dt}. \quad (8)$$

In the case of variable frequency, the center frequency f_0 is replaced with a variable frequency. We first use a center frequency to estimate the instantaneous frequency within the arbitrarily set frequency band using (8). It is reasonable to expect instantaneous frequencies that are changing, especially if the dynamics are highly TV. Thus, we utilize a subsequent variable frequency approach, which accounts for the possible TV nature of instantaneous frequency within the defined frequency bands to obtain a more precise measurement of instantaneous frequency.

By changing the center frequency followed by using the variable frequency approach of (1) and (6), respectively, as well as the LPF, the signal $x(t)$ will be decomposed into the sinusoid modulations by the CDM technique, as follows:

$$x(t) = \sum_i A_i(t) \cos \left(\int_0^t 2\pi f_i(\tau) d\tau + \phi_i(t) \right) + dc(t). \quad (9)$$

The instantaneous frequency and amplitude of A_i can be calculated using the Hilbert transform. The entire time–frequency spectrum can be obtained by the calculation of the Hilbert transform of (9) for all time points for the obtained low-pass-filtered frequency components, as described in (3). Therefore, by the combination of the CDM and Hilbert transform, a high TF resolution spectrum and accurate amplitude information can be obtained.

The procedure for the implementation of the CDM or FFCDM on a TFS is summarized next.

- 1) Design a finite-impulse response (FIR) LPF with the bandwidth and the length of the filter set to F_ω and N_ω , respectively. Set center frequencies as

$$f_{0i} = (i - 1)(2F_\omega), \quad i = 1, 2, \dots, \text{int} \left(\frac{f_{\max}}{2F_\omega} \right). \quad (10)$$

where the bandwidth between neighboring center frequencies is $2F_\omega$, and $f_{\max}$ represents the highest signal frequency.

- 2) Use the FFCDM to extract the dominant frequency within the confined bandwidth and repeat it over the entire frequency band (by incrementing f_{0i}).
- 3) Decompose the signal into sinusoidal modulations via the CDM.
- 4) Calculate the instantaneous frequencies using (8) based on the phase (5) and the instantaneous amplitudes (4) of each sinusoidal modulation component using the Hilbert transform.
- 5) Obtain the TF representation of the signal using the estimated instantaneous frequencies and amplitudes.

For the VFCDM method, only the center frequencies known as the “backbones” of the FFCDM time–frequency spectrum are considered in subsequent analysis. This approach allows a considerable reduction in computation time since only a few frequencies (those of interest) are analyzed. Once we have an estimate of center frequencies, the LPF cutoff frequency can be made even smaller than the first step of the VFCDM. Design a FIR LPF in which the bandwidth of the filter is set to $F_\nu = F_\omega/2$, and the length of the filter is set to $N_\nu = N_\omega$ along the estimated center frequencies $f_i(t)$. We have previously shown that for the VFCDM, the aforementioned choices of the LPF cutoff frequencies and the length of the filter provide good TFS estimates [16].

Extract more refined amplitude and phase information via steps 3–5. These procedures are used to further improve the performance of the TFS.

B. Extraction of Respiratory Rate

In the following sections, we describe three different methods for extracting respiratory rates. Our proposed method VFCDM will be compared to the CWT and AR modeling approaches in Section III.

1) *Extraction of Respiratory Rate Using the VFCDM:* Once the TFS is obtained via the VFCDM method as described before, respiratory rates are determined by extracting the frequency component that has the largest amplitude for each time point at the heart rate frequency band, since this component reflects the FM. This is justified since the FM is a form of fluctuation that is reflected in the subfrequency band of a carrier wave, which in our case is the heart rate. To determine frequencies (e.g., respiratory rate) associated with these oscillations, the power spectrum of the FM sequence is calculated and the frequency at which the highest peak occurs is the desired respiratory rate. A TV spectral method can be used in lieu of the power spectrum if the FM time series is nonstationary. The same procedure is also used for extraction of respiratory rate using the AM.

2) *Extraction of Respiratory Rates Using CWTs:* As recommended by Leonard *et al.* [5]–[7], Addison and Watson [12], [13], and Clifton *et al.* [14], we used a Morlet wavelet with a half-length of five samples at the coarsest scale to estimate the scalogram of the PPG signal. The procedure to extract respiratory rates from the CWT is identical to the VFCDM, as described previously. An important difference between the CWT and CDM methods is that the CWT method employed by Leonard *et al.* [5]–[7], Addison and Watson [12], [13], and Clifton *et al.* [14] essentially selects the best estimate of the breathing rate from the calculated AM and FM estimates. However, they do not explicitly detail how this selection is done. Hence, for comparison purposes, we divided the results into two separate categories: results from CWT-AM and results from CWT-FM calculations.

3) *Extraction of Respiratory Rates Using AR Modeling:* Fleming and Tarassenko have recently developed an AR modeling approach to respiratory rate estimation [15], which models the PPG signal using the Burg algorithm [20]. As such, the PPG signal $x(n)$, where n denotes the number of samples, can be

modeled as a weighted sum of past $x(n)$ values in the following manner:

$$x(t) = - \sum_{k=1}^p a(k)x(n-k) + e(n). \quad (11)$$

The error $e(n)$ is assumed to be normally distributed with zero mean and a variance σ^2 , and can be seen as a driving input to the system, in which case the transfer function of the system can be written as follows:

$$H(z) = \frac{z^p}{(z - z_1)(z - z_2) \cdots (z - z_p)}. \quad (12)$$

The aforementioned transfer function has p complex conjugate poles and no finite zeros. The resonant frequency of each spectral peak is given by the phase angle of that pole as

$$f = \frac{\theta}{2\pi\Delta t}. \quad (13)$$

Here, Δt is the sampling interval of the PPG signal. After calculating the separate resonant frequencies corresponding to every pole, the specific breathing pole is recognized by comparing the magnitudes of the poles, since it is expected that the breathing poles have the highest magnitudes. Only those candidates are chosen that have resonant frequencies in the possible breathing range. Out of these, only that breathing pole is chosen which has the smallest phase angle. For specific details of the preconditioning and pole-selection algorithms, see [15].

C. Data Acquisition

Data were collected on 15 healthy subjects (seven female and eight male, mean age 21 ± 1.2 years) using a MP506 pulse oximeter (Nellcor Oximax, Boulder, CO) reusable sensor (Durasensor DS-100A), which incorporates a conditioning circuit and has an analog output of 4.864 kHz. No subject had cardiorespiratory or related pathologies. Data were collected in the upright and supine positions, and the sensor was attached to the subjects' left index or middle finger. The subjects were instructed to breathe at a constant rate according to a timed beeping sound, i.e., to start an inspiration whenever they heard a beep sound programmed at a chosen frequency. The data were collected for breathing frequencies ranging from 0.2 to 0.6 Hz at an increment of 0.1 Hz. The subjects were given some time to practice breathing at the beeping rate. Three minutes of data were collected for each frequency for each subject, for both upright and supine positions. A true breathing signal was also acquired via the RespiTrace system, which uses inductive plethysmography to provide calibrated voltage outputs corresponding to rib cage and abdominal compartment volume changes. The RespiTrace system is cumbersome to use since inductive bands are worn over the rib cage and abdomen, and the system requires calibration for each subject and it is more expensive than a pulse oximeter. Since in this study we are merely interested in the rate of respiration and not the amplitude, a simple FFT and/or manual counting of the number of peaks can be done on the RespiTrace signal to obtain the frequency of oscillation. Data acquisition was done using the ADInstruments PowerLab/4Sp data acquisition system and routed into the PC via a universal

serial bus (USB) port. Chart v4.2.2 software (ADInstruments, Colorado Springs, CO) was used to sample the analog signal at 200 Hz.

D. Data Analysis

Three minutes of data sampled at 200 Hz were low-pass-filtered to 10 Hz, and then downsampled to 20 Hz. We performed the extraction of the respiratory rate on every 1-min segment of PPG signal, and then the data were shifted by every 10 s for the entire 3 min of recordings, i.e., each 1-min dataset had a 50 s overlap. Hence, for each 3-min segment, we had 13 1-min segments to analyze for all methods to be compared. Thus, 3 min of data were sufficiently long to test the efficacy of each method but not too long in duration to fatigue the subjects as their task was to breathe on cue with a metronome. For the CDM and CWT methods, for every 1-min segment, the initial and final 5 s of the TFS were not considered because the TFS has an inherent end effect that could create false variability. The filter parameters of the VFCDM were set to $F_w = 0.03$ Hz, $F_v = 0.015$ Hz (both are normalized frequencies), and $N_w = 64$. Fig. 2 and Section III illustrate how $F_w = 0.03$ Hz was derived. We have previously shown that the parameter $F_v = F_w/2$, and that N_w is chosen to be approximately half the data length [16].

III. RESULTS

An example of a representative 1-min segment of PPG data and its VFCDM time-frequency spectrum when the subject was breathing at a rate of 0.2 Hz (12 breaths/min) is shown in Fig. 1(a) and (b), respectively. As shown in Fig. 1(a), the periodic oscillations of the PPG signal are nearly periodic, and thus, our use of the CDM approach to model the signal as per (6) is appropriate. Note especially the primary FM seen around 1.5 Hz that corresponds to the heart rate (90 beats/min); other higher frequency peaks (e.g., 3 Hz, 4.5 Hz, etc., are harmonics of 1.5 Hz). Fig. 1(c) shows the extracted FM time series at each time point from the TFS shown in Fig. 1(b), and its subsequent power spectrum is shown in the Fig. 1(d). The largest peak in this power spectrum is the 0.2 Hz, which corresponds correctly to the breathing rate.

The Nyquist frequency in this case is 10 Hz, but we only consider the frequency range from 0.15 to 0.7 Hz. In some cases, peaks were seen at frequencies greater than 0.7 Hz, and they were found to be mainly due to measurement artifacts and harmonics of the $f < 0.7$ Hz dynamics. As a breathing rate more than 0.7 Hz is unrealistic, we ignore the range of frequencies (i.e., $f > 0.7$ Hz) when looking for the highest peaks. Furthermore, no method was able to provide accurate results when the true breathing frequencies were greater than 0.7 Hz. In addition, we excluded breathing rates that are lower than 0.15 Hz since dynamics pertaining to the sympathetic tone are known to be active in the frequency range between 0.04 and 0.15 Hz. For example, if a subject's breathing rate is 0.3 Hz with the sympathetic tone highly innervated, then the largest peak may be located anywhere in the frequency band of 0.04–0.15 Hz instead of the expected respiratory rate peak at 0.3 Hz. It should be noted, however, that the VFCDM method is accurate

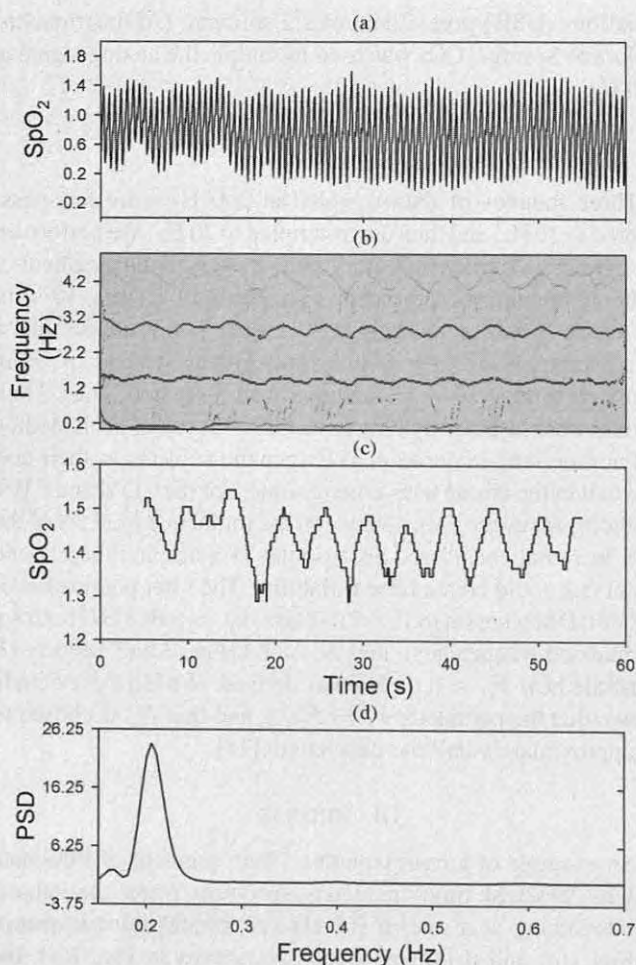


Fig. 1. (a) Representative pulse oximeter signal. (b) Estimated instantaneous frequencies using VFCDM with prominent frequency oscillations seen near heart rate (1.5 Hz). (c) FM sequence extracted from the pulse ridge in the time-frequency plot. (d) PSD of the FM signal. It is clear that the highest peak is obtained at 0.2 Hz, which is same as the breathing frequency (12 beats/min).

even for respiratory rates lower than 0.15 Hz, but we do not provide comprehensive results for breathing rates lower than this since the peaks associated with sympathetic tone could confound detection at higher breathing rates.

For a complete comparison of all these methods, it is necessary to look at differences in results across subjects, across time, across different body positions (supine and upright breathing positions), and across true breathing rate. In order to do this in an effective manner, we divide the results into two broad categories, supine and upright. For each of these categories, percentage detection errors were found for each frequency for all subjects using the four different methods. The percentage error is calculated as follows:

$$\% \text{Error} = \left(\frac{\hat{R} - R}{R} \right) 100. \quad (14)$$

Where $\hat{R}$ denotes the detected breathing rate and R is the true breathing rate. For every subject, we obtained 13 detections (from 3 min recordings with 1 min data analysis window shifted in time by 10 s) for each breathing frequency. The median and

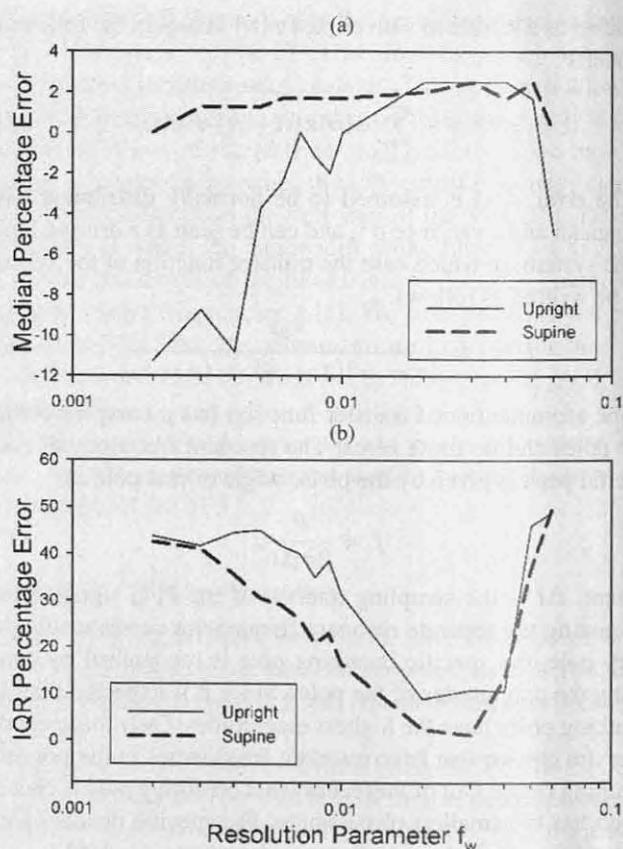


Fig. 2. Semilog plots showing trend of (a) median and (b) IQR of error percentage as a function of the resolution parameter for the VFCDM-FM method. The best results were obtained with regard to both accuracy and spread of error across subjects, frequencies, and positions using a parameter value of 0.03.

interquartile range (IQR) (difference between the 25th and 75th percentile) of the percentage detection errors of these 13 detections were compiled for all four methods for every frequency for every subject. The median value provides an estimate of the accuracy of the method while the IQR gives an estimate of the ability of the algorithm to track the frequency across time (within the data duration of 3 min) for every subject. Hence, a median value that is close to zero would indicate good accuracy of the method studied. Similarly, the smaller the IQR, the better the rate tracking ability or repeatability of the method. These two statistics were compared across the entire population (15 subjects).

It is instructive to observe the change in accuracy and consistency of detection with the variation of the principal resolution-determining parameter for the VFCDM method, i.e., the F_w . Fig. 2(a) shows the variation of the median detection error percentage as the F_w parameter is varied from 0.002 to 0.06 Hz for the supine (dashed line) and upright (solid line) positions. It can be seen that the median error starts from a high negative value and gradually improves to a little above 0% for both body positions before increasing in magnitude again. Similarly, Fig. 2(b) shows the variation of the spread (as measured by the IQR of the percentage error) as the resolution parameter increases over the same range as previously for the supine (solid line) and upright (dotted) positions. Again, it can be seen that the most

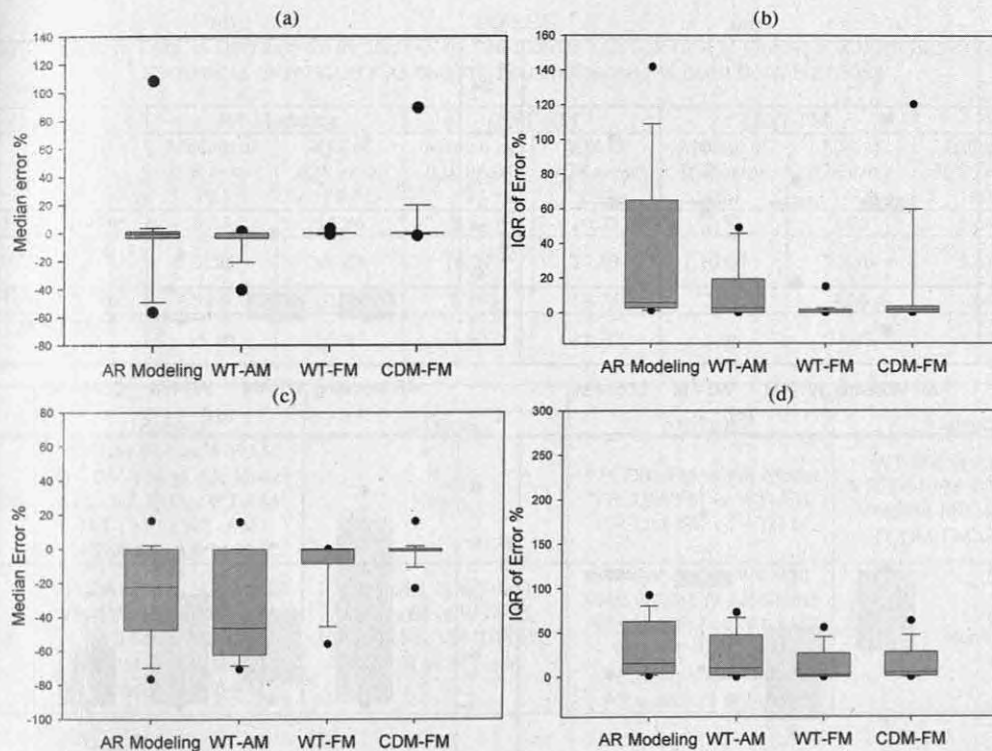


Fig. 3. (Left panels) Median errors and (right panels) IQR errors for the supine position. The top row (a) and (b) are for low breathing frequencies (0.2 and 0.3 Hz), and the bottom row (c) and (d) are for high frequencies (0.4–0.6 Hz). Filled circles above and below each bar graph represent the 95th and 5th percentiles, respectively.

desirable IQR values are obtained for F_w values of 0.02–0.04 for both body positions. Note that the dramatic decrease in IQR variables from F_w is 0.01–0.03 Hz more than compensates for the slight decrease in median errors (a measure of the accuracy) over the same range. For the sake of consistency, we chose a value of $F_w = 0.03$ Hz for our method.

Figs. 3 and 4 show the accuracy and repeatability of each method as a function of true breathing rate for the supine (Fig. 3) and upright (Fig. 4) positions. For tabulating the results, we grouped the results for 0.2–0.3 Hz together and designated them as the LF breathing rates. Likewise, the results for 0.4–0.6 Hz breathing rates were lumped together and designated as the HF breathing rates. Statistical testing (using an ANOVA on ranks) was done to see if there were significant differences between the medians for the four different methods. In addition, a Brown–Forsythe test was used to compare the variances across the population. Since the percentage errors obtained were found to be not normally distributed, we used median, IQR, and nonparametric tests like ANOVA on ranks, and the Brown–Forsythe test instead of the mean, standard error, and parametric tests such as one-way ANOVA or Levene test (for variance).

Figs. 3 and 4 show the subjects' variation of the median (left panels) and IQR (right panels) of percentage detection error for the supine and upright positions, respectively, in the form of box plots. The top and bottom panels of Figs. 3 and 4 represent results for the LF and HF breathing rates, respectively. The lower boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the upper boundary of the box farthest from zero indicates the 75th

percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Hence, the gray area of the box is an indication of the spread, i.e., the variation in median error (or IQR), across the population. These figures indicate how well the algorithms perform across the entire population. Solid circles represent the 5th and 95th percentiles. The top panels of Tables I and II summarize these measures of accuracy (median) and “repeatability across time” (IQR), respectively, by tabulating the median and IQR of these statistics across the population for both supine and upright positions. The bottom panels of Tables I and II provide a summary of statistical analysis comparing the performance of the four methods to each other.

The AR model approach is the least accurate followed by CWT-AM, CWT-FM, and VFCDM when we consider all body positions and all breathing frequencies. For LF breathing rates, there was no significant difference in the median error between all four methods for both body positions as they were all accurate. However, the variances of the median values as determined by the IQR of median error are significantly lower for both VFCDM and CWT-FM than for either CWT-AM or AR model approaches.

In general, the median error is larger in HF than LF breathing rates. For HF breathing rates, the median error is lowest for VFCDM, followed by CWT-FM, CWT-AM, and AR model for both body positions. While there is no significant difference in the variance between VFCDM and CWT-FM, both methods have significantly less variance than either CWT-AM or AR model. Thus, gauging the accuracy as defined by the median

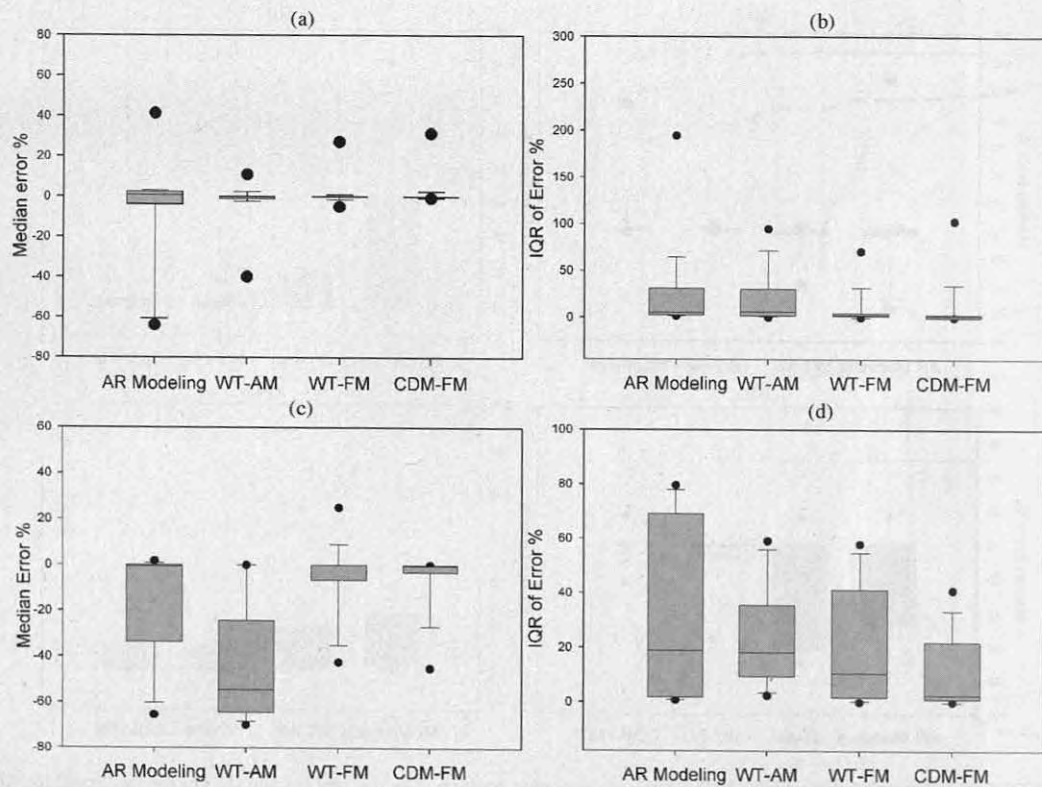


Fig. 4. (Left panels) Median errors and (right panels) IQR errors for the upright position. The top row (a) and (b) are for low breathing frequencies (0.2 and 0.3 Hz) and the bottom row (c) and (d) are for high frequencies (0.4–0.6 Hz). Filled circles above and below each bar graph represent the 95th and 5th percentiles, respectively.

TABLE I
(TOP) ACCURACY AS DETERMINED BY MEDIAN ERRORS AND IQR OF MEDIAN ERRORS FOR BOTH BODY POSITIONS. (BOTTOM) STATISTICAL SIGNIFICANCE AMONG THE FOUR METHODS FOR BOTH BODY POSITIONS

Position	True Breathing Rate (Hz)	AR Modeling		CWT-AM		CWT-FM		VFCDM-FM	
		Median of median error (%)	IQR of median error (%)	Median of median error (%)	IQR of median error (%)	Median of median error (%)	IQR of median error (%)	Median of median error (%)	IQR of median error (%)
Upright	LF(0.2-0.3Hz)	0.81	5.12	0.00	1.12	0.00	0.07	0.00	0.07
	HF(0.4-0.6 Hz)	-0.67	27.29	-54.47	39.02	0.00	4.98	-0.39	2.52
Supine	LF(0.2-0.3Hz)	-0.57	3.69	0.00	3.05	0.00	0.00	0.00	0.0977
	HF(0.4-0.6 Hz)	-22.14	43.85	-46.53	61.50	-0.39	1.37	0.00	1.12

	LF		HF	
	Medians	Variances	Medians	Variances
Upright	None	WT-FM vs WT-AM VFCDM-FM vs WT-AM	WT-FM vs WT-AM WT-FM vs AR model WT-FM vs VFCDM-FM VFCDM-FM vs WT-AM AR model vs WT-AM	AR model vs WT-AM AR model vs VFCDM-FM WT-FM vs WT-AM VFCDM-FM vs WT-AM
Supine	None	AR model vs WT-AM WT-FM vs WT-AM VFCDM-FM vs WT-AM	VFCDM-FM vs WT-AM VFCDM-FM vs AR Model VFCDM-FM vs WT-FM WT-FM vs WT-AM WT-FM vs AR Model AR model vs WT-AM	AR model vs WT-AM WT-FM vs WT-AM VFCDM-FM vs WT-AM

errors and their variances, as shown in the left panels of Figs. 3 and 4, and presented numerically in the top panel of Table I, we observe that for both LF and HF breathing rates, VFCDM consistently provides the lowest median errors and variance values.

Repeatability or consistency of the four methods is shown in the right panels of Figs. 3 and 4, and numerically in the top panel of Table II. In general, the ability of the methods to provide consistent results is especially excellent (highest) for both the CWT-FM and VFCDM methods, for both LF and HF breathing

TABLE II

(TOP) REPEATABILITY ACROSS TIME AS DETERMINED BY MEDIAN OF IQR ERRORS AND IQR OF IQR ERRORS FOR BOTH BODY POSITIONS. (BOTTOM) STATISTICAL SIGNIFICANCE AMONG THE FOUR METHODS FOR BOTH BODY POSITIONS

Position	True Breathing Rate (Hz)	AR Modeling		CWT-AM		CWT-FM		VFCDM-FM	
		Median of IQR error (%)	IQR of IQR error (%)	Median of IQR error (%)	IQR of IQR error (%)	Median of IQR error (%)	IQR of IQR error (%)	Median of IQR error (%)	IQR of IQR error (%)
Upright	LF(0.2-0.3Hz)	5.33	15.84	6.51	26.21	2.50	3.25	1.64	3.27
	HF(0.4-0.6 Hz)	18.91	66.84	18.29	24.59	10.64	39.16	2.47	19.77
Supine	LF(0.2-0.3Hz)	5.69	61.96	2.44	16.78	1.62	1.64	1.64	3.27
	HF(0.4-0.6 Hz)	15.16	55.52	9.80	41.70	1.96	25.49	4.88	25.25

	LF		HF	
	Medians	Variances	Medians	Variances
Upright	VFCDM-FM vs WT-AM VFCDM-FM vs AR Model VFCDM-FM vs WT-FM WT-FM vs WT-AM WT-FM vs AR Model	None	VFCDM-FM vs AR Model VFCDM-FM vs WT-AM VFCDM-FM vs WT-FM	WT-FM vs AR model VFCDM-FM vs AR Model VFCDM-FM vs WT-AM VFCDM-FM vs WT-FM
Supine	VFCDM-FM vs AR Model VFCDM-FM vs WT-FM WT-FM vs WT-AM WT-FM vs AR Model AR model vs WT-AM	AR model vs WT-AM AR model vs WT-FM AR model vs VFCDM-FM WT-FM vs WT-AM	VFCDM-FM vs WT-AM VFCDM-FM vs AR Model VFCDM-FM vs WT-FM WT-FM vs WT-AM WT-FM vs AR Model AR model vs WT-AM	None

rates and body positions. As with the accuracy results, the repeatability is also better for the LF than for the HF breathing rates for all four methods. Both CWT-FM and VFCDM provide significantly more repeatable results than either CWT-AM or AR model.

IV. DISCUSSION

In this study, we demonstrated the accuracy of a novel approach to extract respiratory rates from pulse oximeter recordings. The method was shown to be accurate for widely varying breathing rates, and can be implemented in real time. We compared our method to both wavelet and AR-based approaches since these two techniques are among the most accurate algorithms to date [15]. Overall, our method based on the use of VFCDM to extract FM signals followed by the power spectrum to extract the respiratory rate is the most accurate and with the fastest computational time than any of the methods compared for both supine and upright positions. The continuous wavelet approach using either the FM or AM signals fared better than the AR method for both body positions at the expense of larger computational time.

Estimation of respiratory rate is important in monitoring of patients, whether at home or in a hospital facility. Due to the highly labor-intensive and sometimes invasive nature of accurate respiratory rate estimation, we aimed to develop an algorithm to extract respiration rate from the pulse oximeter, a noninvasive, easy-to-use device intended for measurement of oxygen saturation level. The work by Addison *et al.* [5]–[7], Shelley *et al.* [8], Addison and Watson [12], [13], and Clifton *et al.* [14] is noteworthy since it is one of the first studies to use a time-frequency approach, as opposed to the time domain approaches using filtering methods [9]–[11], [21], [22] to estimate respiratory rates using the pulse oximeter. A time-frequency method

is ideally suited for studying the pulse oximeter signal because of the inherent nonstationarity in the respiratory rate. In addition, a filtering approach usually involves tuning of a number of parameters that pose a problem when signal characteristics vary from subject to subject. While Fleming and Tarassenko [15] do mention a decrease in accuracy when the AR modeling approach is used on 30-s segments (real-time implementation) instead of 5-min segments, we found that this decrease was far greater than that obtained with time-frequency approaches.

Our method is similar to the work by Addison *et al.* [5]–[7], Addison and Watson [12], [13], and Clifton *et al.* [14] in that we also estimate the TFS of the PPG signal, but differs from them since we only use the FM signals and not both AM and FM signals, and a different TFS estimation method is used. The reason why Addison *et al.* used both AM and FM signals is that the accuracy of the extracted respiratory rate was better with FM in some cases while the AM provided better results in other instances [5]–[7], [12]–[14]. We also found that this was the case with our results using the wavelet approach. They suggested the use of an *ad hoc* approach to determine when to select either the AM or FM results; however, the details on implementation of this decision procedure are not available in any of their published works.

Instead of a wavelet approach, we used our recently developed VFCDM method that was shown to provide one of the highest time-frequency resolutions [16]–[18]. Hence, we anticipated that using this approach in estimating the TFS would yield better results in respiratory rate estimation than the wavelet approach used by Addison *et al.* [5]–[7], Addison and Watson [12], [13], and Clifton *et al.* [14]. While we are also able to extract respiratory rate from both AM and FM signals, we found that the results on the AM signals were not as reliable as the FM signals. In a way, this is a good news since we do not have to use some complicated decision scheme to determine when

to use the results of AM or FM. As shown in both Figs. 3 and 4, and Tables I and II, the respiratory rate detection using the FM signals derived from the wavelet method provided better results than AM signals in most cases for both body positions. Thus, similar to our approach, a case can be made that the wavelet method can also use only the FM signals to extract the respiratory rates. Even with such a scheme, the VFCDM approach provides better estimates of the respiratory rates in most cases.

Another advantage of our algorithm is that the estimation of TFS is considerably faster than the wavelet method. The average time to calculate the respiration frequency using the VFCDM method was found to be around 0.3 s, while using the Wavelet method took 2 s on average (programs running on MATLAB R2007b). This means that a real-time implementation of the algorithm would be considerably faster and easier using the VFCDM method. The AR spectral method was the fastest as it took 0.1 s on average using MATLAB, and this computation time includes the time needed to calculate the model order based on an initial model order selection of 50.

In contrast to the findings by Leonard *et al.* [7], we did find the existence of rate-dependent error in detection of breathing rate. This is probably because Leonard *et al.* used longer segments of the PPG signal in their study (180 s compared to 60 s for this study). In addition, the study in [7] compared detection accuracies for breathing rates only as high as 27 breaths/min (0.45 Hz). In this study, it was observed that for both wavelet and VFCDM methods, and for both supine and upright conditions, detection of the respiratory frequency became less accurate with increase in actual breathing rate. However, for the upright condition, the VFCDM method provides better respiration rate estimate than the WT-FM or WT-AM methods. Note that the most accurate results were obtained for respiration frequencies 0.2 and 0.3 Hz. It should be noted that the normal range of breathing rate falls in this range, and breathing rates higher than 0.5 Hz are rare. Hence, we anticipate that this method of breathing frequency extraction should perform quite well in most cases. In fact, for very high breathing rates, the method would at least serve to give a clear indication of deviation from normal frequency, even if it is not able to estimate the frequency itself with very high accuracy.

We can speculate about the reason for less accurate results with higher respiratory rates seen in our study with all algorithms tested. Detection of both AM and FM requires persistent oscillations for several cycles, but with faster respiratory rates, this condition may not hold. In addition, with faster breathing rates, the amplitudes of AM or FM become less, and thus, it becomes more difficult to detect them. Thus, a higher resolution-based TFS method such as the VFCDM is required to work better with higher respiratory rates; such was the case in our paper.

A. Limitations

We have limited our study to healthy subjects to demonstrate the feasibility of the proposed approach. Detection of accurate respiratory rates may not be optimal for subjects with certain cardiovascular diseases that increase sympathetic tone.

For example, subjects with a pacemaker or on heart rhythm changing medications may lead to less accurate respiratory rate detection using our approach. For all other subjects, however, we believe that the method proposed in this paper is feasible.

Literature also supports our claim. A work by Clifton *et al.* [14] has reported accurate respiratory rate detection in subjects with respiratory problems, as well as in subjects under general anesthesia and recovering from it, using the same CWT method as compared in our paper. In addition, a work by Leonard *et al.* [7], and a work by Fleming and Tarassenko [15] have reported accurate respiratory rate detection in children with spontaneous breathing using the CWT and AR modeling approaches, respectively. Thus, given the fact that we have used the same CWT and AR modeling methods, as in the aforementioned studies, for comparisons to our method, we believe that our method will be as accurate in healthy young and adult subjects with spontaneous breathing, subjects with respiratory problems, and in patients during anesthesia and post anesthesia. Furthermore, for most healthy and unhealthy subjects described before, their spontaneous breathing rates fell within 0.2–0.4 Hz [14], and given our accurate detection in these rates, it is not unreasonable to assume that our method will be just as accurate or better than the case of spontaneous breathing rates.

The Mayer wave oscillation often seen in spontaneous arterial pressure has a characteristic frequency of ~ 0.1 Hz in humans, and is enhanced during the state of sympathetic activation [23]. For this reason, we did not provide results on respiratory rates lower than 0.15 Hz, since the peaks associated with sympathetic tone (0.04–0.15 Hz) could confound detection at higher breathing rates. Note that spectral peaks in the range of 0.04–0.15 Hz arise due to the actions of the sympathetic tone [24] or Mayer waves at ~ 0.1 Hz [23]; thus, detection of respiratory rates will be suboptimal if a subject has events that elevate the sympathetic activities or the presence of Mayer waves such that their spectral peaks are larger than the respiratory peak.

In this paper, we tested the performance of the VFCDM method against metronome breathing and not spontaneous breathing. The metronome breathing allowed us to estimate near real-time performance of the algorithm as our results are based on 1-min data segments that are shifted every 10 s. In our opinion, spontaneous breathing masks give the true performance of the algorithms since the results in the literature are often reported based on the averaged respiratory rates as they vary over the duration of 3 min [5]–[7], [12]–[14]. Thus, rather than comparing the results based on the averaged respiratory rate over the entire duration of the data segment, we believe that our choice of reporting the results based on each 10 s shift provides better assessment of the algorithms as well as their near real-time performances. In addition, we can better gauge the true performance of the algorithms since the subjects are breathing at a frequency equal to or very close to the “metronomic” respiratory rate.

In summary, we demonstrated a real-time realizable and consistently accurate approach to extract respiratory rates from direct recordings of the pulse oximeter using the VFCDM approach. The CWT-FM method also provides good results but its computational speed is about seven times slower than VFCDM.

The novelty of either VFCDM or CWT-FM not only resides in our ability to extract accurate respiratory rates, but also in the fact that we can obtain an additional clinically important parameter from the pulse oximeter. Thus, with the pulse oximeter, we can obtain not only the oxygen saturation levels and heart rate, but also the respiratory rates. We believe that this is important because the pulse oximeter is a proven technology that is widely accepted in practice, and the ability to extract multiple vital signs from a single sensor will facilitate enhancements not only from a technical standpoint but, most importantly, from the point of patients' comfort, since they do not have to wear multiple sensors to obtain the same vital sign information.

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Ex-1010

Kurtosis, Renyi's Entropy and Independent Component Scalp Maps for the Automatic Artifact Rejection from EEG data

Antonino Greco, Nadia Mammone, Francesco Carlo Morabito, and Mario Versaci

Abstract—The goal of this work is to improve the efficiency and the reliability of the automatic artifact rejection, in particular from the Electroencephalographic (EEG) recordings. Artifact rejection is a key topic in signal processing. The artifacts are unwelcome signals that may occur during the signal acquisition and that may alter the analysis of the signals themselves. A technique for the automatic artifact rejection, based on the Independent Component Analysis (ICA) for the artifact extraction and on some high order statistics such as kurtosis and Shannon's entropy, was proposed some years ago in literature. In this paper we enhance this technique introducing the Renyi's entropy. The performance of our method was tested exploiting the Independent Component scalp maps and it was compared to the performance of the method in literature and it showed to outperform it.

Keywords—Artifact, EEG, Renyi's entropy, Independent Component Analysis, kurtosis.

I. INTRODUCTION

THE goal of this work is to improve the efficiency and the reliability of the automatic artifact rejection, in particular from Electroencephalographic signals (EEG) recordings. EEG is a technique for monitoring the electrical activity of the brain: the brain cells communicate by producing electrical impulses and, by means of some electrodes held on the scalp over multiple areas of the brain, we can detect and record patterns of this electrical activity. Some flat metal discs (electrodes) are applied in different positions on the scalp (see Fig. 1), these discs are held in places with a sticky paste, the electrodes are connected by wires to an amplifier and a recording machine.

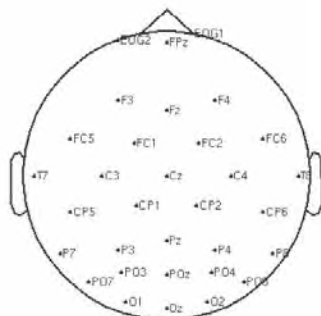


Fig. 1 The EEG electrode montage (32-channels)

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EEG monitoring helps to diagnose the presence and type of seizure disorders, to look for causes of confusion, and to evaluate head injuries, tumors, infections, degenerative diseases and metabolic disturbances that affect the brain. Artifacts are disturbances caused by eye movement, eye blink, electrode movement, muscle activity, movements of the head, sweating, breathing, earth beat, electrical line noise and so on. The occurrence of the artifacts may alter the analysis or completely obscure the EEG waves. When an artifact occurs during the acquisition of a signal, it generates some unwelcome signals that may overlap to the signals that we want to analyse, therefore it may undermine the results of the analysis. In this paper we focus on the automatic artifact rejection from EEG signals.

Many efforts have been devoted to artifact cancellation and in general two approaches have been adopted so far: the cancellation of the entire data segment affected by artifacts (in the following named *artifact-laden trials*), which implies throwing away both the useful and the artifactual information or, when we cannot afford to lose any information from the recorded data, the second approach consists in isolating the artifactual signals and then in cancelling them. In this paper we focus on the second approach.

It is well accepted that an artifact is independent from the rest of the signals, this is clear when the artifact is "external" (electrical line noise), it is also well accepted if it is "internal" (muscle activity, eye blink, etc.) because even though the triggering event starts from a brain area (for example the motor cortex) the time course of the artifact carries no information about the triggering event signal. The spectrum of the signals related to muscle activity contains high frequencies and it can spread from low frequencies to high frequencies; therefore, it can be overlapped to the spectrum of the brain waves, which goes from 0.5 up to 35 Hz, sometimes up to 50 Hz, this high frequency contribution can be weakened by a lowpass filtering.

Since it is accepted that the artifactual signals are independent from the rest, it is also well accepted that the artifactual signals can be extracted by Independent Component Analysis (ICA). ICA has been widely exploited as a tool for artifactual signals extraction, since it was proposed by Cichocki et al. [1] and Jung et al. [2]. The artifactual signal is isolated by ICA as a component independent from the rest.

In order to make the artifacts rejection procedure automatic we need some markers capable to measure how much an independent component (IC) is likely to be an artifactual signal. Delorme et al. [3] proposed the joint use of kurtosis and entropy as markers, while Vorobyov et al. [4] proposed the

Hurst exponent. Delorme et al. [3] proposed the joint use of kurtosis and entropy, in particular the Shannon's entropy, for the detection of the artifactual signals, once they have been isolated by means of ICA. This method had shown to be promising and, since we were interested in automatic artifact rejection, we decided to test and try to enhance it. The test showed some failures of the procedure in detecting some artifactual signals, thus we wondered whether another entropy definition could improve the performance of the method and we decided to introduce the Renyi's entropy. At first, the artifactual signals are isolated, by means of Extended-INFOMAX algorithm for ICA, then the joint use of kurtosis and Renyi's entropy, rather than Shannon's entropy, is proposed.

The paper is organized as follows: Section II describes the application of ICA to the EEG data and the Extended-INFOMAX algorithm [5], Section III introduces the parameters for automatic detection and Section IV presents the results.

II. INDEPENDENT COMPONENT ANALYSIS

A. ICA and EEG Data

Independent component analysis was originally developed to deal with problems that are closely related to the cocktail-party problem. Since many real observations can be assumed to be a mixing of "sources", ICA was exploited for a lot of applications, for example for EEG data. The EEG data are presumably generated by mixing some underlying brain activity related signals and artifacts. This situation is quite similar to the cocktail-party problem: we would like to find the original components of the brain activity, but we can only observe mixtures of the components.

It is worth to wonder whether there are independent sources in the EEG data or not, we told above that it is a shared opinion that at least the artifacts can be considered independent from the rest. The second assumption for standard ICA is that each channel collects a linear combination of the sources, this assumption is well accepted for the EEG sensors, because the different electrical sources (brain activations, muscle activations) are supposed to sum linearly at the scalp electrodes.

B. The Extended-INFOMAX Algorithm

Given an input data vector $\mathbf{x}$, we consider it generated as a mixture of n statistically independent sources $(s_1, \dots, s_n)$:

$$\mathbf{x} = \mathbf{f}(\mathbf{s}) \quad (1)$$

If $\mathbf{f}$ is a linear function, we deal with the *linear* ICA problem:

$$\mathbf{x} = \mathbf{A}\mathbf{s} \quad (2)$$

ICA is a tool for multivariate data analysis which yields $(y_1, \dots, y_n)$ components as independent as possible so that $\mathbf{y} = \mathbf{W}\mathbf{x}$, and $\mathbf{W}$ is close to $\mathbf{A}^{-1}$.

Here we focus on the Bell-Sejnowski *INFOMAX* algorithm [5]. The input of the network is the observed data $\mathbf{x}$, the output

is $\mathbf{y}$, whose elements are the estimated independent components $(y_1, \dots, y_n)$.

The *marginal entropy* of each estimated component is defined as follows:

$$H(y_i) = -E\{\log p(y_i)\} \quad (3)$$

The *joint entropy* has the following expression:

$$H(\mathbf{y}) = -E\{\log p(\mathbf{y})\} = -\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} p(\mathbf{y}) \log p(\mathbf{y}) d\mathbf{y} \quad (4)$$

The *mutual information* is defined as:

$$I(\mathbf{y}) = \int p(\mathbf{y}) \log \frac{p(\mathbf{y})}{\prod_{i=1}^N p_i(y_i)} d\mathbf{y} \quad (5)$$

The relationship between marginal entropy, joint entropy and mutual information is:

$$H(\mathbf{y}) = H(y_1) + \dots + H(y_N) - I(y_1, \dots, y_N) \quad (6)$$

Therefore the components of $\mathbf{y}$ are as independent as possible when their mutual information is minimum. The marginal entropies are constant when $(y_1, \dots, y_n)$ have uniform distribution and are amplitude bounded random variables, so while minimizing mutual information we maximize joint entropy. Maximizing joint entropy leads to the INFOMAX learning rule [5]:

$$\Delta \mathbf{W} \propto [\mathbf{I} - \phi(\mathbf{y})\mathbf{y}^T] \mathbf{W} \quad (7)$$

Where

$$\phi(\mathbf{y}) = -\frac{\frac{\partial p(\mathbf{y})}{\partial \mathbf{y}}}{p(\mathbf{y})} \quad (8)$$

is called *score function* and p is the joint probability density function of $\mathbf{y}$.

INFOMAX has the limitation to assume that the sources have super-gaussian distributions and at most one source is normally distributed, therefore, Extended-INFOMAX was introduced to separate sources with a variety of distributions. Since Renyi's entropy, as we will describe in Section III, depends on sources distribution, we needed to know whether a source was sub-gaussian or super-gaussian, therefore we used the extended version of INFOMAX. A way of generalizing the learning rule is to consider an approximation of the estimated pdf of the sub-gaussian and the super-gaussian sources, this leads to extended learning rule is [5]:

$$\Delta \mathbf{W} \propto [\mathbf{I} - \mathbf{K} \tanh(\mathbf{y})\mathbf{y}^T - \mathbf{y}\mathbf{y}^T] \mathbf{W} \quad (9)$$

There are two different learning rules for sub-gaussian and super-gaussian sources, the switching criterion between the two rules is given by $\mathbf{K}$: it is a N-dimensional diagonal matrix whose elements are:

$$k_{ii} = \begin{cases} 1 & \text{when } y_i \text{ is super-gaussian} \\ -1 & \text{when } y_i \text{ is sub-gaussian} \end{cases}$$

these elements are estimated as part of the algorithm. Extended-INFOMAX yields the independent components and the unmixing matrix $\mathbf{W}$, to reconstruct the observed signals we compute:

$$\tilde{\mathbf{x}} = \mathbf{W}^{-1}\mathbf{y} \quad (10)$$

in order to reconstruct the cleaned signals, we have to suppress the alleged artifactual components and to compute the (10).

III. AUTOMATIC ARTIFACT DETECTION

Artifacts are outlier data, in other words transient and unexpected events; therefore we need some markers to measure this oddness to detect outlier trials or outlier independent components (ICs) once we have extracted them by ICA. The markers proposed by Delorme et al. [3] are kurtosis and entropy, which are both related to the distribution of the signals.

A. Kurtosis as a Marker for Artifacts

In some trials, the distribution of the components is very peaky, for instance during a transient strong muscle activity, so the kurtosis can help us to detect these artifacts. Given a scalar random variable x , kurtosis has the following expression:

$$k = m_4 - 3m_2^2 \quad (11)$$

$$m_n = E\{(x - m_1)^n\} \quad (12)$$

where m_n is the n -order central moment of the variable and m_1 is the mean. Kurtosis is positive for "peaked" activity distributions, typical of eye blink and cardiac artifacts; kurtosis is negative for "flat" activity distributions, typical of noise [3].

In order to detect artifactual components, kurtosis was computed for each trial and for all the ICs and it was normalized, to 0-mean and standard deviation 1, with respect to all the ICs, the threshold was set at ± 1.64 [6], if a component exceeded the threshold in more than 20% of the trials, the component was marked for rejection because it was very likely to be an artifact.

Kurtosis can also be exploited to detect the components which were very likely to account for gaussian noise: we estimated the kurtosis of the pdf of each component (global kurtosis), the IC with the minimum positive coefficient was marked as gaussian noise.

B. Entropy as a Marker for Artifacts

As a second marker we used the differential entropy:

$$H(x) = -\int p_x(\xi) \log(p_x(\xi)) d\xi \quad (13)$$

The entropy can be interpreted as a measure of randomness: if the random variable is concentrated on small temporal intervals, its differential entropy is small, indeed the variables whose probability densities take large values give a strong contribution to the integral in the (13), so their entropy is small. This feature of the entropy helps us to identify the signals which are concentrated in small temporal intervals with high probabilities and, therefore, which are very likely to be artifacts.

An approximation of the (13) was used:

$$H^i(j) = -\sum_{x \in j} f_j^i(x) \log(f_j^i(x)) \quad (14)$$

which is the entropy of the IC_i in the trial j , and $f_j^i(x)$ is the pdf of the component IC_i during trial j .

In order to detect the artifactual components, entropy was computed for each trial and for all the ICs and it was normalized, to 0-mean and standard deviation 1, with respect to all the ICs, the threshold was set at ± 1.64 [6], if a component exceeded the threshold in more than 20% of the trials, the component was marked for rejection because it was very likely to be an artifact.

We want to compare the performances of the Shannon's entropy (14) and the Renyi's entropy. Renyi's entropy depends on a parameter α and, for a random variable y with a pdf $f_y(y)$, it is defined as:

$$H_{R_\alpha}(y) = \frac{1}{1-\alpha} \log \int_{-\infty}^{+\infty} f_Y(y) dy = \frac{1}{1-\alpha} \log E\{f^{\alpha-1}(y)\} \quad (15)$$

The Parzen window pdf estimate of a random variable y for which only the samples $\{y_1, \dots, y_N\}$ are given, is defined by:

$$\hat{f}(y) = \frac{1}{N} \sum_{i=1}^N k_\sigma(y - y_i) \quad (16)$$

where $i = 1 \dots N$ and k_σ is the gaussian kernel, whose size is specified by σ (we chose $\sigma = 0.25$).

When we substitute the real pdf with the approximation (16) in the (15) we have:

$$H_{R_\alpha}(y) = \frac{1}{1-\alpha} \log \left[\frac{1}{N^\alpha} \sum_j \left(\sum_i k_\sigma(y - y_i) \right)^{\alpha-1} \right] \quad (17)$$

The pdf's were estimated by the Parzen windowing method in both the Shannon's entropy and the Renyi's entropy computation.

All the properties stated in Section III.B are for both Shannon's entropy and Renyi's entropy and therefore they help us to identify the signals which are concentrated in small temporal intervals with high probabilities, for both artifact-laden trials and artifactual components. The automatic detection procedure, described in the Section III.B, was used for Renyi's entropy and each trial coincides with a Parzen window. We tested the automatic detection of the artifactual components for $\alpha = 2$ in order to study the behaviour of the Renyi's entropy because we know that, for super-Gaussian sources, entropy orders ≥ 2 should be preferred, whereas for sub-Gaussian sources, entropy orders smaller than 2, perhaps closer to 1 or even smaller than 1, should be preferred [7].

Entropy orders larger than 2 emphasize samples in concentrated regions of data, whereas smaller orders emphasize the samples in sparse regions of data. If the mixtures belong to different kurtosis classes, the quadratic entropy can be employed as it puts equal emphasis on all data points regardless of their probability density.

IV. RESULTS

We used a benchmark [8] to test the procedure, it consists on 32-channels EEG data (Fig. 2) sampled at 128 Hz, we extracted the first 24 seconds data segment because it is known that INFOMAX algorithm provides N reliable components (for N channel data) if we process at least $3N^2$ data samples, in this case $N = 32$, therefore we have to process at least 3072 samples (24 seconds) [8]. We removed the electrical line noise by a notch filter at 60Hz and we set the width of each Parzen window at 200, therefore we had 15 data segments (trials). Thus, we had to reject an IC if the markers computed for that IC exceeded the fixed threshold in more than 20% of the trials, therefore in at least 4 trials.

The ICs and the scalp maps of the projection of the ICs on the electrode sites were obtained by EEGLAB [8].

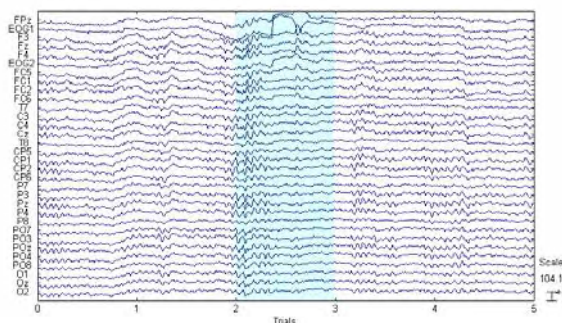


Fig. 2 The EEG data. During trial 3 (highlighted) the early channels are affected by ocular artifacts

We processed the data by Extended-INFOMAX and the ICs are plotted in Fig. 3. The scalp map projection of the ICs was estimated thanks to EEGLAB and is depicted in Fig. 4, this map helps us in localizing the activation of the ICs and in detecting those ICs whose activation is concentrated on one

electrode, as the activation of the ocular artifacts is. Looking at the distribution of the activation of each IC, we can realize that IC10 has the typical eye blink artifact projection, IC9 has the typical eye movement projection. IC14 and IC20 seem to account for eye movement too. The ocular artifact can be identified thanks to scalp maps because the intensity of their activation is high in the frontal electrodes, in particular, the activation of the eye blink artifact is concentrated in a spot whereas the activation of the eye movement is a bit more spread.

Once the ICs were extracted, kurtosis, Shannon's entropy and Renyi's entropy were computed for each trial for each IC, as described in Section III, they are plotted in Fig. 5. Table I summarizes the automatic detection.

Kurtosis detected IC10, Shannon's entropy detected IC2, IC10, IC17, IC21, IC24, Renyi's entropy detected IC1, IC2, IC9, IC10, IC17, IC21, IC24. Global kurtosis detected IC14 which accounts for an amount of the eye movement artifact.

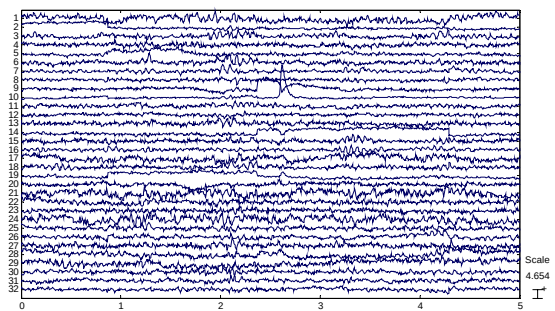


Fig. 3 The Independent Components. By a visual inspection we can realize that IC9 has the typical eye movement artifact shape and that IC10 surely accounts for eye blink

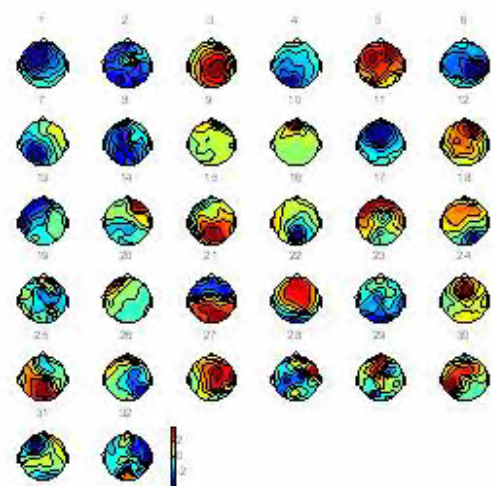


Fig. 4 The scalp map of the projection of the ICs. IC9 accounts for eye movement artifact, IC10 accounts for eye blink artifact, IC14 and IC20 are likely to account for a bit of the eye movement too

Thus, the joint use of kurtosis and Shannon's entropy detected IC2, IC10, IC14, IC17, IC21, IC24, whereas the joint use of kurtosis and Renyi's entropy detected IC1, IC2, IC9, IC10, IC14, IC17, IC21, IC24. IC9 was detected only by our method, and it is certainly an eye movement artifact. IC1 was detected only by our method too, and it looks like a muscular artifact. IC19 which accounts for a little amount of the eye movement too, but it was not detected by any of the two methods.

In Fig. 6, the cleaned dataset is depicted, it was reconstructed cancelling the ICs detected by the joint use of kurtosis and Renyi's entropy, the artifacts appear suppressed.

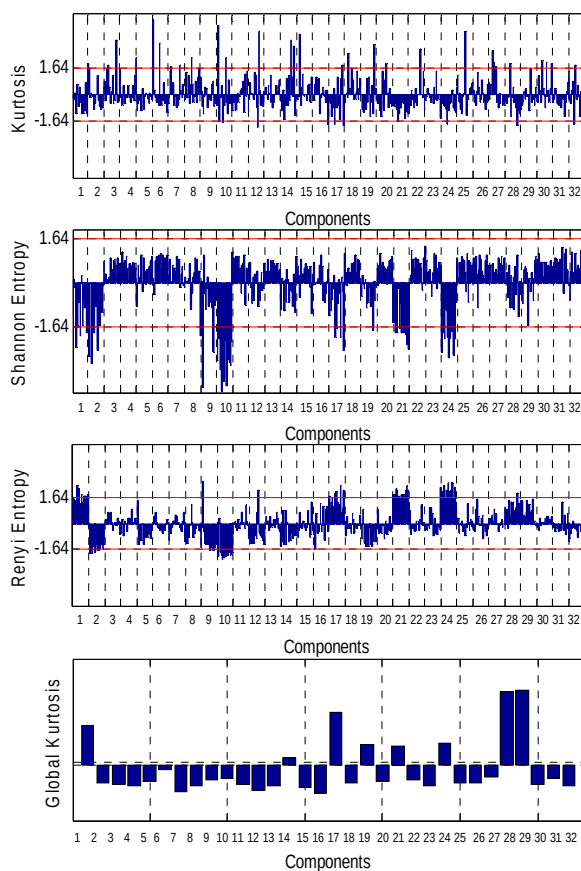


Fig. 5 The automatic artifact detection. Kurtosis detected IC10, which accounts for eye blink artifact. Shannon's entropy detected IC2, IC10, IC17, IC21, IC24. Renyi's entropy detected IC1, IC2, IC9, IC10, IC17, IC21, IC24. Global kurtosis detected IC14. IC9 was detected only by the proposed method, and it is certainly an eye movement artifact. IC1 was detected only by our method too, and it looks like a muscular artifact

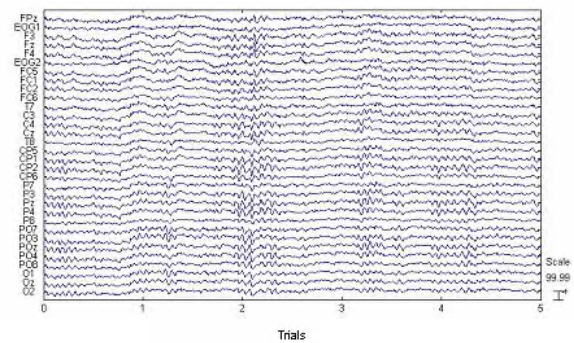


Fig. 6 The reconstructed EEG data. The ICs marked according to kurtosis and Renyi were suppressed and the data reconstructed by the Eq (10). Trial 3 appears free from the artifacts

V. CONCLUSIONS

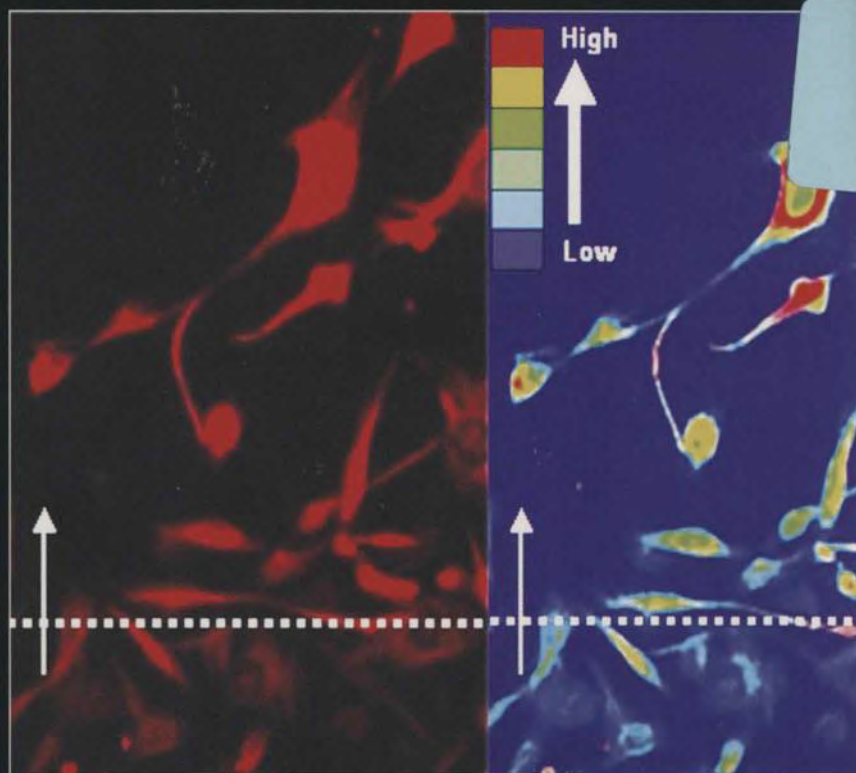
Artifact rejection is a key topic in biomedical signal processing and in literature, Independent Component Analysis (ICA) has shown to be a suitable tool for extracting the artifactual signals and some higher order statistics, kurtosis together with Shannon's entropy, have been used as markers for the automatic artifact detection. In this paper we have proposed the joint use of kurtosis and Renyi's entropy, rather than Shannon's entropy, and we have tested the reliability of the procedure comparing its results with the results of the visual inspection of the shape of the independent components and of the component scalp maps. The joint use of kurtosis and Renyi's entropy showed to outperform the joint use of kurtosis and Shannon's entropy. Future efforts will be devoted to enhance the reliability of the procedure focusing on artifactual signal extraction.

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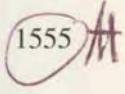
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Cover: Migration of cultured aortic Vascular Smooth Muscle Cells (VSMC) from transgenic mice (Tgp22^{phox}), in which p22^{phox} is overexpressed, was visualized focusing on wound edge (white dashed line) area. Cells were stained by Myosin Heavy Chain embryonic (SMemb) immunocytochemistry (red colored, left figure). The white arrow indicates migration direction toward the wound-scratched area. The image was converted from plain (left figure) to range scaled plate (right figure) to indicate the level of fluorescence intensity representing SMemb expression in each sing cell. The continuous color change from blue to red represents expression of SMemb from low to high levels. Mostly, VSMC at the wound area showed higher SMemb expression than non-migration area.

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Estimation of Time-Varying Coherence Function Using Time-Varying Transfer Functions

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Abstract—We introduce a new method to estimate reliable time-varying coherence functions (TVCF) for causal systems. The technique is based on our previously developed method to estimate time-varying transfer functions (TVTF), known as the time-varying optimal parameter search algorithm [Zou, R., H. Wang, and K. H. Chon. A robust time-varying identification algorithm using basis functions. *Ann. Biomed. Eng.* 31: 840–853, 2003]. The TVCF is estimated by the multiplication of two TVTFs. The two TVTFs are obtained using signal x as the input and signal y as the output to produce the first TVTF, and signal y as the input and signal x as the output to produce the second TVTF. Demonstration of the feasibility and efficacy of the proposed approach is provided with both simulation examples and application to renal blood flow and pressure data. The proposed approach provides higher time-frequency resolution TVCF than afforded by the short time Fourier transform based TVCF.

Keywords—Time-varying transfer function, Time-varying coherence function, ARMA, Time-varying, Renal autoregulation.

INTRODUCTION

Applications of the time-frequency distribution (TFD) have had a tremendous impact in understanding dynamic processes of various physiological systems. Physiological systems are inherently time varying (TV), thus, immediate acceptance of the TFD-based methods by the biomedical and biological communities was readily expected. Recently, new methods were introduced to compute time-varying transfer functions (TVTF) that have the potential to further advance the understanding of the dynamic processes underlying physiological systems.^{13,14} The characterization of physiological systems with the TVTF is important because the admittance gain between input and output signals is correctly characterized to be transient, and not stationary, as is assumed with the time-invariant transfer function.

In this paper, we utilize a parametric (model based, e.g., autoregressive moving average (ARMA) model) TVTF to estimate the TV coherence function (TVCF). Currently, the

estimation of the TVCF is mainly based on the use of the short-time Fourier transform (STFT) where the ratios between the magnitudes of the TV cross spectrum and the TV auto spectra of the two signals are calculated. Two disadvantages of the STFT are the assumption that time segments are stationary and the limited time-frequency resolution, which preclude the STFT being the method of choice in obtaining accurate and high resolution TVCF. Furthermore, the STFT suffers from high variance. Consequently, the likelihood of obtaining statistical significance of the coherence value is diminished. Recent separate works by Xu *et al.*,¹¹ and Lovette and Ropella⁸ have alleviated the high variance problem of the STFT by introducing multiple window time-frequency (TF) analysis. However, the inherent problem of limited resolution with the STFT was not improved by this approach, but in fact the variance reduction scheme had the undesired effect of further reducing the TF resolution.

As in the time-invariant case, high-resolution TF spectra, TVTF, and TVCF can be obtained via parametric approaches. Arnold *et al.*¹ have developed a parametric TV spectrum and TVCF by means of Kalman filtering. In their work, a parametric TV cross spectrum was obtained by reformulating an ARMA process into a vector AR model, from which the vector TV autospectrum between two signals were obtained. The accuracy of any time-invariant and TV parametric approaches greatly hinges on the proper choice of the model order. In the work by Arnold *et al.*,¹ determination of a model order was not discussed.

An accurate approach for estimating the TVCF is greatly needed, because even today many investigators still resort to time-invariant coherence function analysis.^{2,3,10} The coherence function is important because it provides information as to how two signals are phase-coupled or “coherent” with each other. For most physiological systems, it is expected that the coherence between two signals is not the same throughout the time duration of a data set. Thus, the TVCF is expected to reveal more accurate insights into the time-varying nature of the coupling between two signals. In this work, we propose a different parametric method to estimate TVCF than the approach proposed by Arnold *et al.*¹

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Our approach is based on the algorithm termed time-varying optimal parameter search (TVOPS), which we have recently developed for estimating TVTF.^{13,14} The TVOPS has been shown to be effective in selecting only the significant time-varying model terms, and is more accurate than the two most well-established model order criteria: the Akaike Information criterion (AIC) and the minimum description length (MDL).⁹

The proposed approach is presented in the Methods section. Illustrative simulation examples as well as the application of the proposed method to experimental data are presented in the Results section to demonstrate the feasibility and efficacy of the proposed approach.

METHODS

In this section, we demonstrate that the TVCF can be obtained by using the TVTF relationships. To demonstrate the use of the TVTF in obtaining the TVCF, we first define the TVCF via the nonparametric time-frequency spectra:

$$|\gamma(t, f)|^4 = \frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)} \frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)} \quad (1)$$

where $S_{xy}(t, f)$ and $S_{yx}(t, f)$ represent the time-frequency cross spectrum, and $S_{xx}(t, f)$ and $S_{yy}(t, f)$ denote the autospectra of the two signals x and y , respectively. The above expression $\frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)}$ is the coherence function when x is considered as the input and y as the output while $\frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)}$ is the coherence function when y is considered as the input and x as the output. We note that for a linear time-varying system with x and y as the input and output signals, respectively, the following TVTF in terms of time-frequency spectra can be obtained:

$$H_{x \rightarrow y}(t, f) = \frac{S_{xy}(t, f)}{S_{xx}(t, f)} \quad (2)$$

where $H_{x \rightarrow y}(t, f)$ denotes the TVTF from the input x to the output y signals. Similarly, if we reversed the input and output relationship such that the variables y and x represent input and output signals, respectively, as Fig. 1 depicts, then the following TVTF can be obtained:

$$H_{y \rightarrow x}(t, f) = \frac{S_{yx}(t, f)}{S_{yy}(t, f)} \quad (3)$$

The desired relationship of Eq. (1) can be obtained by multiplying the two TVTF relationships of Eqs. (2) and (3), which yields:

$$\begin{aligned} & |H_{x \rightarrow y}(t, f)H_{y \rightarrow x}(t, f)|^2 \\ &= \left| \left(\frac{S_{xy}(t, f)}{S_{xx}(t, f)} \right) \left(\frac{S_{yx}(t, f)}{S_{yy}(t, f)} \right) \right|^2 = \left| \left(\frac{S_{xy}(t, f)}{S_{xx}(t, f)} \right) \left(\frac{S_{yx}(t, f)}{S_{yy}(t, f)} \right) \right|^2 \\ &= \left[\frac{|S_{xy}(t, f)|^2}{S_{xx}(t, f)S_{yy}(t, f)} \right] \left[\frac{|S_{yx}(t, f)|^2}{S_{yy}(t, f)S_{xx}(t, f)} \right] \\ &= |\gamma(t, f)|^4 \end{aligned} \quad (4)$$

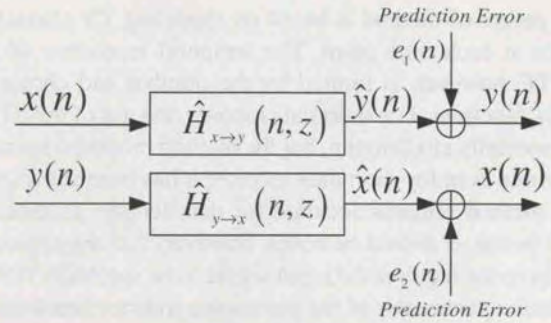


FIGURE 1. Block diagram of two procedures involved in calculation of time-varying coherence function.

Thus, time-varying magnitude squared coherence, $|\gamma(t, f)|^2$, is then obtained by multiplying the two transfer functions, $|H_{x \rightarrow y}(t, f)H_{y \rightarrow x}(t, f)|$, together.

Given the relationship of Eq. (4), we can obtain a high resolution TVCF via the parametric TVTF. Specifically, each of the two transfer functions in Eq. (4) can be obtained using autoregressive moving average (ARMA) models:

$$\begin{aligned} y(n) &= - \sum_{i=1}^{P_1} a(n, i)y(n-i) + \sum_{j=0}^{Q_1} b(n, j)x(n-j) \\ x(n) &= - \sum_{i=1}^{P_2} \alpha(n, i)x(n-i) + \sum_{j=0}^{Q_2} \beta(n, j)y(n-j) \end{aligned} \quad (5)$$

where the top expression in Eq. (5) represents $y(n)$ and $x(n)$ as the output and input, respectively, and the reverse for the bottom expression of Eq. (5). Our definition of the ARMA model refers to two measured signals of $y(n)$ and $x(n)$. Given the ARMA models of Eq. (5), the two transfer functions of Eq. (4) can be obtained by the following:

$$\begin{aligned} H_{x \rightarrow y}(n, e^{j\omega}) &= \frac{B(n, e^{j\omega})}{A(n, e^{j\omega})} = \frac{\sum_{j=0}^{Q_1} b(n, j)e^{-j\omega j}}{1 + \sum_{i=1}^{P_1} a(n, i)e^{-j\omega i}} \\ H_{y \rightarrow x}(n, e^{j\omega}) &= \frac{\beta(n, e^{j\omega})}{\alpha(n, e^{j\omega})} = \frac{\sum_{j=0}^{Q_2} \beta(n, j)e^{-j\omega j}}{1 + \sum_{i=1}^{P_2} \alpha(n, i)e^{-j\omega i}} \end{aligned} \quad (6)$$

In this paper, we obtain an accurate and high resolution TVTF of Eq. (6) by the previously-developed approach, termed the TVOPS.^{13,14}

In two references^{13,14}, it was demonstrated that more accurate estimate of the TVTF can be obtained than of the STFT, including an example concerning TV amplitude modulated signals. Furthermore, because the method proposed does not utilize segmentation of the data records, as is the case with the STFT, neither time nor frequency resolutions are compromised. Note that for the proposed approach, the TVTF, and consequently the TVCF, are obtained for every time point and are based on a few parameters chosen by the TVOPS from the initially-selected model orders P_1, Q_1, P_2 and Q_2 in Eq. (6). Therefore, while the STFT assumes that each segment of data is stationary,

the proposed method is based on modeling TV characteristics at each time point. The temporal resolution of the TVTF, however, is limited by the number and choice of basis functions. For short data records, the use of the STFT is especially challenging, but the method proposed remains accurate even for short data records; it has been shown that the method remains accurate for data lengths as short as 500 points. It should be noted, however, that the approach we propose requires the input signal to be spectrally rich to estimate parameters of the parametric transfer functions.

An abbreviated version of the algorithm for estimating TVTF via the TVOPS is outlined in the Appendix section. For full details of the TVOPS algorithm, the reader is referred to.^{13,14}

In the proceeding section, we show that theoretical values of TVCF are bounded in the interval of zero to one. To illustrate, consider two signals modeled by the following equations:

$$\begin{aligned} y(n) &= \hat{h}_{x \rightarrow y}(n) * x(n) + e_1(n) \\ x(n) &= \hat{h}_{y \rightarrow x}(n) * y(n) + e_2(n) \end{aligned} \quad (7)$$

Here, $e_1(n)$ and $e_2(n)$ are prediction error terms that are uncorrelated to $y(n)$ and $x(n)$, respectively, and $*$ denotes the convolution operator. Taking the Fourier transform on both sides of Eq. (7) yields:

$$\begin{aligned} S_{yy} &= |\hat{H}_{x \rightarrow y}|^2 S_{xx} + S_{e_1} = |\hat{H}_{x \rightarrow y}|^2 S_{xx} + \sigma_{e_1}^2 \\ S_{xx} &= |\hat{H}_{y \rightarrow x}|^2 S_{yy} + S_{e_2} = |\hat{H}_{y \rightarrow x}|^2 S_{yy} + \sigma_{e_2}^2 \end{aligned} \quad (8)$$

Note that:

$$\begin{aligned} |S_{xy}| &= |\hat{H}_{x \rightarrow y} S_{xx}| \\ |S_{yx}| &= |\hat{H}_{y \rightarrow x} S_{yy}| \end{aligned} \quad (9)$$

Substituting the expressions in Eq. (8) and Eq. (9) into Eq. (1):

$$\begin{aligned} |\gamma(t, f)|^4 &= \frac{|S_{xy}|^2 |S_{yx}|^2}{S_{xx} S_{yy} S_{yy} S_{xx}} \\ &= \frac{|\hat{H}_{x \rightarrow y}|^2 S_{xx}^2}{S_{xx} (|\hat{H}_{x \rightarrow y}|^2 S_{xx} + \sigma_{e_1}^2)} \frac{|\hat{H}_{y \rightarrow x}|^2 S_{yy}^2}{S_{yy} (|\hat{H}_{y \rightarrow x}|^2 S_{yy} + \sigma_{e_2}^2)} \\ &= \frac{|\hat{H}_{x \rightarrow y}|^2 S_{xx}^2 |\hat{H}_{y \rightarrow x}|^2 S_{yy}^2}{(|\hat{H}_{x \rightarrow y}|^2 S_{xx}^2 + S_{xx} \sigma_{e_1}^2) (|\hat{H}_{y \rightarrow x}|^2 S_{yy}^2 + S_{yy} \sigma_{e_2}^2)} \\ &= \frac{|\hat{H}_{x \rightarrow y}|^2 S_{xx}^2 |\hat{H}_{y \rightarrow x}|^2 S_{yy}^2}{S_{xx}^2 S_{yy}^2 |\hat{H}_{x \rightarrow y}|^2 |\hat{H}_{y \rightarrow x}|^2 + S_{xx}^2 S_{yy} |\hat{H}_{x \rightarrow y}|^2 \sigma_{e_2}^2 + S_{yy}^2 S_{xx} |\hat{H}_{y \rightarrow x}|^2 \sigma_{e_1}^2 + S_{xx} S_{yy} \sigma_{e_1}^2 \sigma_{e_2}^2} \\ &= \frac{1}{1 + \frac{\sigma_{e_2}^2}{S_{yy} |\hat{H}_{y \rightarrow x}|^2} + \frac{\sigma_{e_1}^2}{S_{xx} |\hat{H}_{x \rightarrow y}|^2} + \frac{\sigma_{e_1}^2 \sigma_{e_2}^2}{S_{yy} |\hat{H}_{y \rightarrow x}|^2 S_{xx} |\hat{H}_{x \rightarrow y}|^2}} \\ &= \frac{1}{1 + \frac{1}{SNR_1} + \frac{1}{SNR_2} + \frac{1}{SNR_1 SNR_2}} < 1 \end{aligned} \quad (10)$$

For simplicity, the time and frequency arguments have been omitted in Eq. (10).

As Eq. (10) indicates, the value of $|\gamma(t, f)|^4$ is bounded by 1. Note that when signal-to-noise ratios SNR_1 and SNR_2 approach ∞ , $|\gamma(t, f)|^4$ tends to 1, and when SNR_1 and SNR_2 approach zero, $|\gamma(t, f)|^4$ tends to zero.

As shown above, theoretically $|\gamma(t, f)|^4$ is bounded by 1. However, when the estimated transfer functions have poles lying on the unit circle, the value of $|\gamma(t, f)|^4$ may be greater than one. Note that because the system is time-varying, the poles are also naturally time-varying. When a pole is initially stable but becomes unstable (or vice versa), it will cross the unit circle periphery, as it moves from interior to exterior or vice versa. If this occurs, the magnitude of the transfer function becomes infinite. As a consequence, $|\gamma(t, f)|^4$ will have a value greater than one. Under this circumstance, the coherence relationship between two signals is undefined because the system undergoes a transition from stable to unstable or vice versa.

Stability only places restriction on the poles and not the zeros. For the inverse system (one with system function $1/H(z)$), the poles become zeros and vice versa, thus, for the minimum phase system where both poles and zeros are inside the unit circle, the maximum TVCF values will be no larger than a unit value. Thus, in the event where the estimated transfer functions do not satisfy a minimum phase system, the TVCF will also have values greater than one.

The top panel of Fig. 2 shows an example of the time course of poles, which drift from instability into stability, and the resultant coherence function estimate is provided in the bottom panel of Fig. 2. During the first 390 s, the magnitudes of the three poles have values outside the unit circle and consequently, coherence values are greater than one during this time period, as shown in the bottom panel of Fig. 2(b). As the poles cross over from the unstable to stable condition (at the instant poles cross the unit circle), even higher coherence values at two distinct frequencies are observed at time points centered around 400 s.

It should be noted that, in certain circumstances, the method might yield greater than unit coherence values beyond the frequency band of interest. This situation may arise because signal dynamics are missing in these frequency bands, which can lead to erroneous coherence values. However, this is trivial and can be effectively ignored since

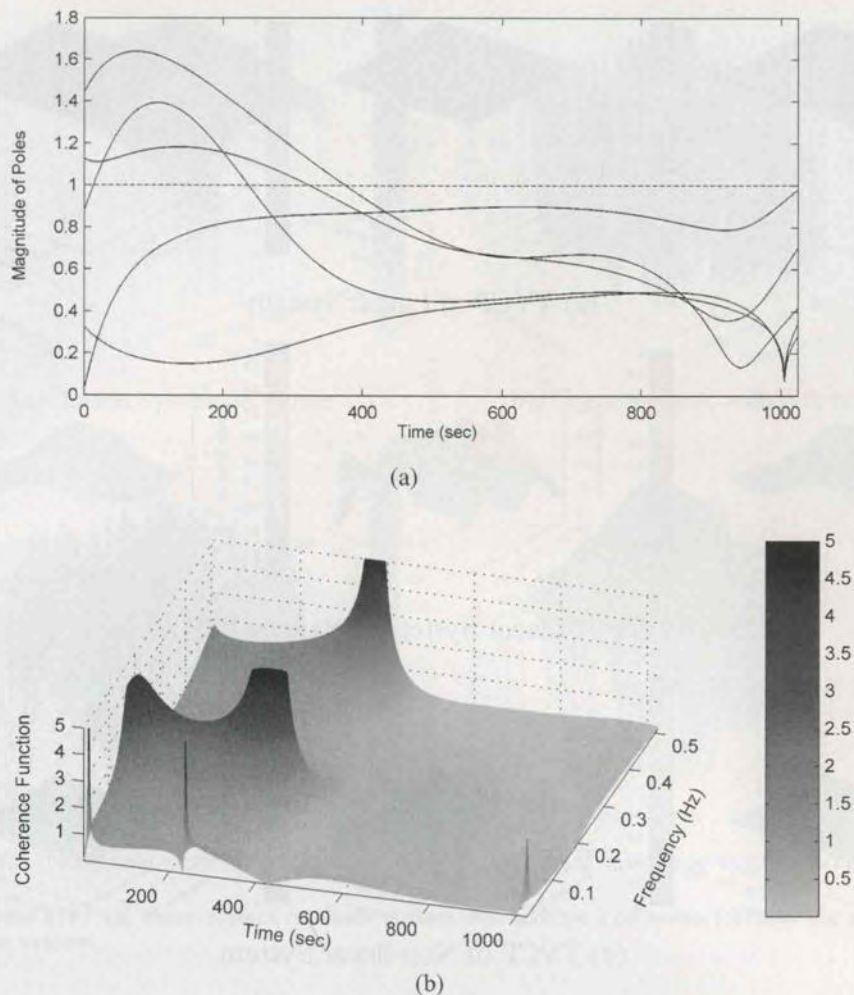


FIGURE 2. Poles crossing over the unit circle introduces high values in the estimated coherence function. (a) Magnitude of poles of the estimated transfer functions (b) Estimated time-varying coherence function.

the coherence values are not in the frequency range of interest.

RESULTS

Simulation examples are used to demonstrate both the feasibility and efficacy of the proposed method for obtaining the TVCF. In particular, the expected decrease of TV coherence values with noise and nonlinearity are demonstrated with 100 Monte Carlo realizations. The plots shown in Figs. 3–5 are results of one single realization, while the averaged results are reported in Table 1. With the use of the previously-developed TVOPS algorithm to compute the TVTF, three parameters that need to be preset are the number of Legendre functions, the model order and the threshold value. Based on these three preset parameters, TVOPS determines only those model orders that are deemed to be significant among initial candidate model terms. Details regarding this procedure are provided in the Appendix section as well as in references.^{13,14} For

both simulation examples and application of the method to the experimental data, we used the Legendre basis functions based on our *a priori* knowledge that underlying dynamics do not change abruptly. For fast-changing dynamics, more appropriate basis functions to use would be the Walsh functions. The threshold value is used for the linear independent candidate term search, as this value is dependent on the signal-to-noise ratio as well as on whether the signal is colored or white. Since *a priori* knowledge of the aforementioned conditions is unknown, we normally set the threshold value to 0.0001 and 0.001 for clean and noise-corrupted signals, respectively. Thus, for simulation examples and experimental data analyses to follow, we set the number of Legendre functions to 5 and the threshold value to 0.0001 for a noiseless simulation example and 0.001 for those cases (including experimental data) that are contaminated by noise. To determine the proper number of basis functions, we have modified the Akaike Information criterion to:

$$\text{AIC} = N \log \sigma^2 + 2[p \cdot k + 1] \quad (11)$$

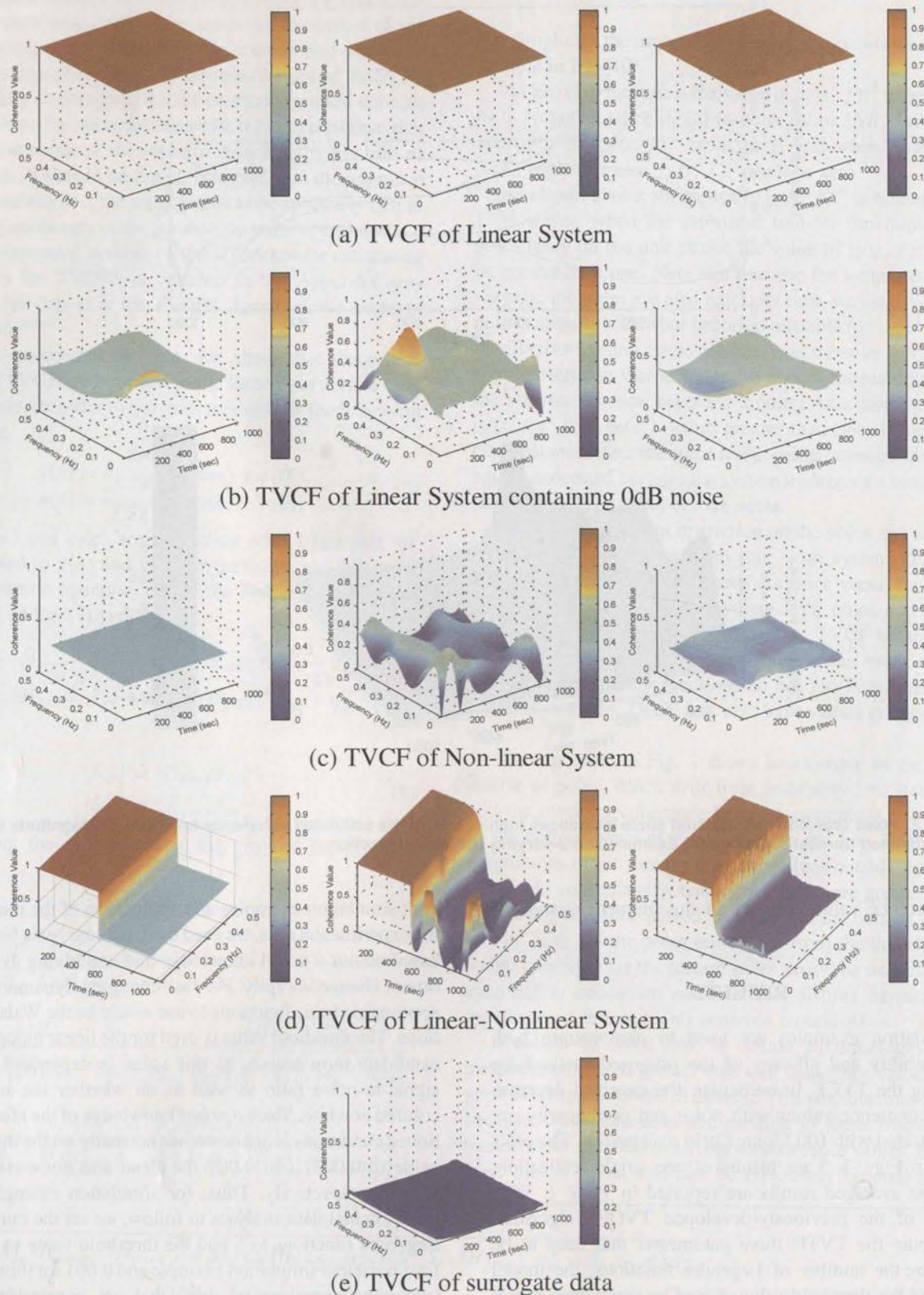


FIGURE 3. The left panels are the theoretical TVCF values; the middle panels are the TVCFs via TVOPS based on a single realization; and the right panels are the averaged TVCFs via TVOPS based on 100 realizations. (a) linear system, (b) linear system with additive 0 dB noise, (c) nonlinear system, (d) linear system followed by nonlinear system, (e) surrogate data of combined linear and nonlinear systems shown in (d).

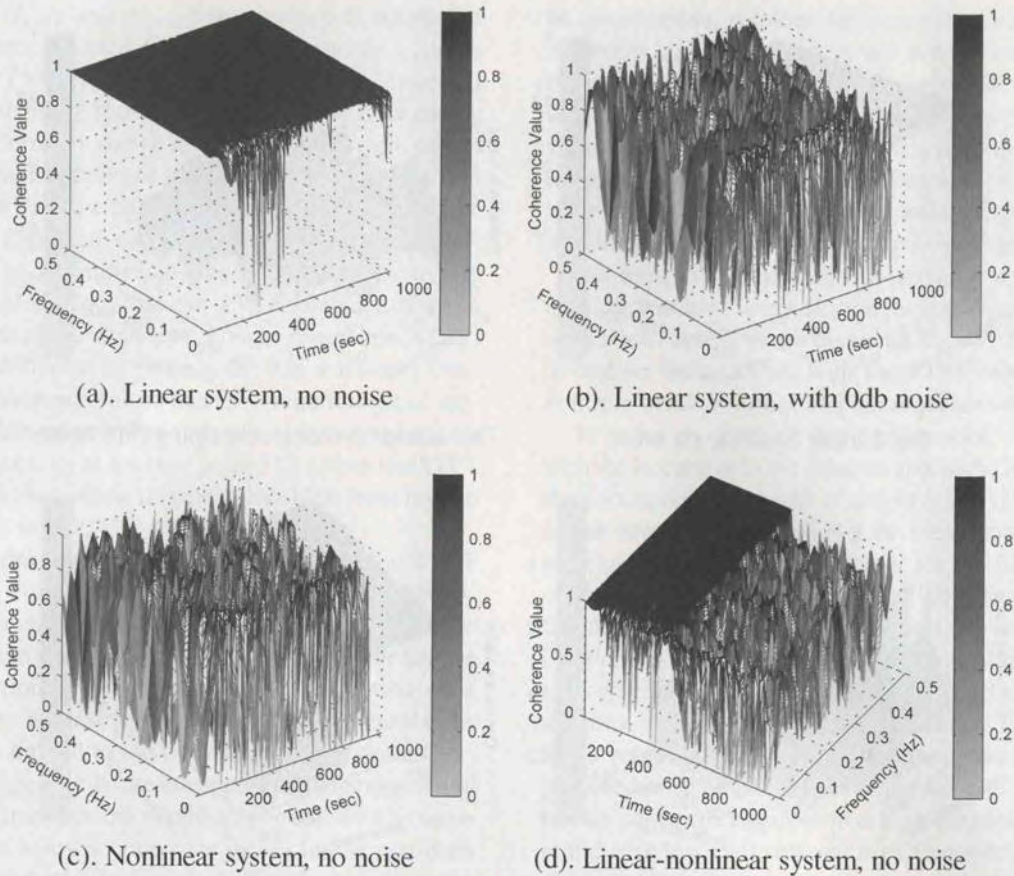


FIGURE 4. TVCF via the STFT: (a) linear system, (b) linear system with additive 0 dB noise, (c) nonlinear system, (d) linear system followed by nonlinear system.

where N is the data length, σ^2 is the prediction error, p is the number of significant terms (not to be confused with the maximum model order), k denotes the number of basis functions. The minimum value of the AIC is used as the criterion for determining the proper number of basis functions among the initially-chosen V sets of basis functions.

Simulation Examples

For the first simulation example, the following TV expression ($N = 1024$) was generated with a sampling rate of 1 Hz:

$$y(n) = a_1(n)y(n-1) + a_2(n)y(n-2) + x(n) \quad (12)$$

with

$$\begin{aligned} a_1(n) &= 0.3 \sin(2\pi n/N) + 0.2 \\ a_2(n) &= 0.09 \sin(2\pi n/N) + 0.15 \end{aligned} \quad (13)$$

where x and y are the input and output signals, respectively. TVOPS was employed to estimate the transfer functions (both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$) with an initial model order of ARMA(6, 6) from which only 4 (out of 13) and 3 (out of 13) significant model terms were selected by the TVOPS for the estimation of $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$, respectively. For

the above expression, because it is linear, TV, and without noise corruption, we expect the TVCF to be of unit value for all times, as shown in the left panel of Fig. 3(a). Indeed, the TVCF values, shown in the middle (based on a single realization) and right (averaged over 100 realizations) panels of Fig. 3(a), have near unit values across all times and frequencies (see Table 1). For all plots in Fig. 3, the left, middle and right panels represent, in order, the theoretical values, a single realization estimated via the TVOPS, and the averaged estimates from applying the TVOPS to multiple realizations. The middle and right panels of Fig. 3(b) show the decrease of coherence values across all times and frequencies, as expected, when Eq. (12) is contaminated with 0 dB Gaussian White noise (GWN) that is time invariantly added to the output of Eq. (12). There is a good agreement with the estimated TVCF values and the theoretical value (0.44) shown in the left panel of Fig. 3(b). To further demonstrate another scenario of decrease in TVCF values, the following nonlinear expression was generated:

$$y(n) = a_1(n)y(n-1) + a_2(n)y(n-2) + x(n) + x^2(n) \quad (14)$$

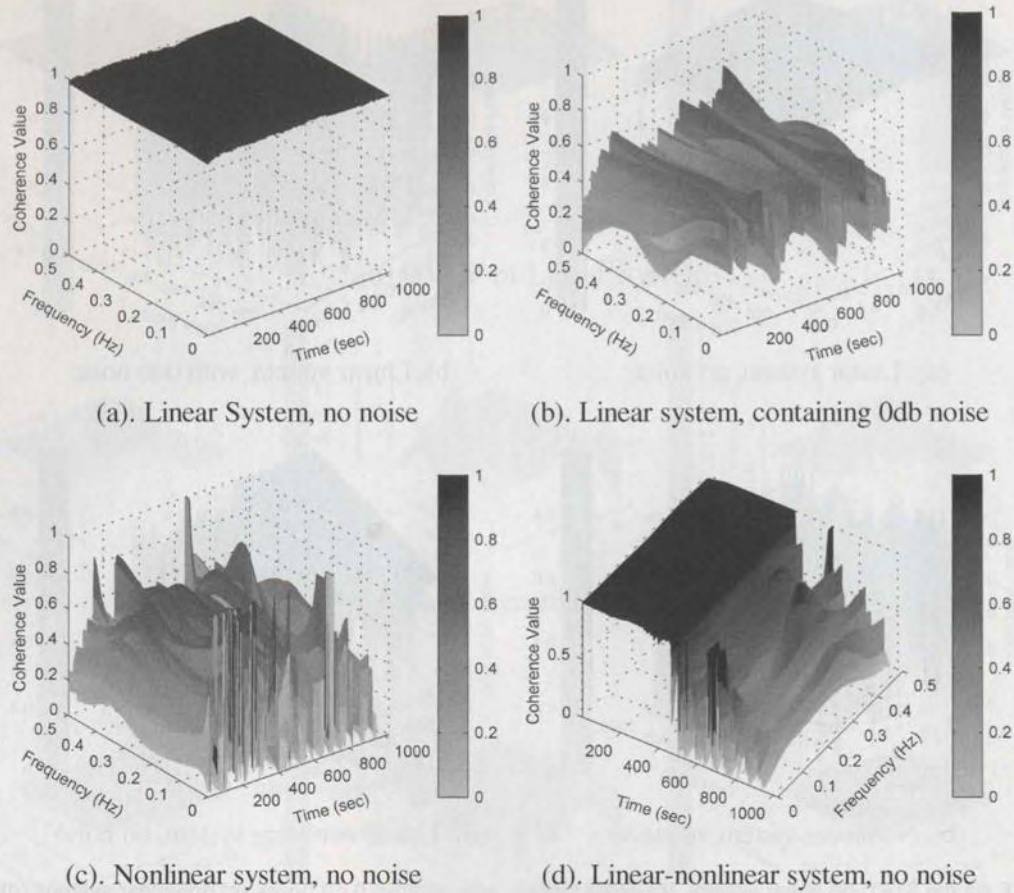


FIGURE 5. TVCF via the RLS: (a) linear system, (b) linear system with additive 0 dB noise, (c) nonlinear system, (d) linear system followed by nonlinear system.

The initial model order was set to ARMA(6, 6) (for both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$) from which a total of 4 and 6 significant model terms were selected for the estimation of $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$, respectively. The linear terms in Eq. (14) are the same as shown in Eq. (12). Note in Fig. 3(c) the significantly lower coherence values than in the linear case, for all times and frequencies, due to the overall TV nonlinearity of the system response of Eq. (14). The estimated TVCF values

shown in the middle and right panels correspond well to the theoretically expected TVCF value (0.33) shown in the left panel of Fig. 3(c).

The next simulation example considers the time course of a noiseless TV linear and nonlinear system as described by Eqs. (12–14). The linear dynamic (Eqs. (12, 13)) occurs from 0 to 512 s and the nonlinear dynamic (Eq. (14)) occurs thereafter. The initial model order was set to ARMA(6,

TABLE 1. Mean and standard deviations of coherence function.

Methods	Cases				
	Linear	0 db noise	Nonlinear	Linear-nonlinear	
				$t = 1$ to 512	$t = 513$ to 1024
TVOPS	1.00 ± 0.01	0.44 ± 0.04	$0.32 \pm 0.01^*$	0.97 ± 0.03	$0.14 \pm 0.01^*$
STFT	0.99 ± 0.02	$0.62 \pm 0.07^*$	$0.59 \pm 0.05^*$	0.98 ± 0.07	$0.60 \pm 0.06^*$
RLS	0.99 ± 0.01	0.43 ± 0.02	$0.36 \pm 0.03^*$	0.97 ± 0.01	$0.39 \pm 0.03^*$

Note. No statistically significant differences were observed between the three methods under the conditions reported in columns 2 (linear, noise free) and 5 (before the onset of nonlinearity). Student-Newman-Keuls test was performed; * denotes $p < 0.05$.

6) (for both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$) from which 6 significant parameters were selected for both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$. The results of the TVCF for this combination of TV linear and nonlinear systems are shown in the middle and right panels of Fig. 3(d). Correctly shown in the middle and right panels of Fig. 3(d), high coherence values are observed from 0 to 512 s followed by low coherence values thereafter. Thus, the proposed approach, due to its high-resolution capability, is able to show transition from high coherence to low coherence values. Note that the TVCF obtained using a technique such as the short time Fourier transform (STFT) would have difficulty in pinpointing this transition from high to low coherence values due to its requirement of segmenting the data record. For example, if the segmentation did not occur exactly at the time point 512 s, then the STFT would not be able to show this clear transition from high to low coherence values.

For the middle and right panels of Fig. 3(d), the TVCF values for the nonlinear period are lower than the theoretical value, shown in the left panel in Fig. 3(d). This lower coherence value is due to greater prediction error for the nonlinear portion of the signal. Greater prediction error results because we restrict the estimated parameters to be linear and are limited to the 6 most significant parameters for the entire signal, thus, the linear portion of the signal will be better captured than the nonlinear portion, which consequently results in lower coherence values for the nonlinear portion of the signal. In Fig. 3(c), TVCF values via the TVOPS are very close to the theoretical value, since all the selected parameters were solely devoted to fitting nonlinear data. The RLS estimated TVCF values, shown in Fig. 5(d), are closer to the theoretical value because RLS uses far more parameters than does the TVOPS. For example, the RLS uses 6 parameters at each time instant, resulting in a total of 6144 parameters, whereas the TVOPS uses only 72 parameters for the entire data.

To further demonstrate the efficacy of the proposed method, we applied the method to surrogate data, which was generated from the input and output of Eqs. (12–14) (a linear and nonlinear system). The initial model order was set to ARMA(6, 6) (for both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$) from which 4 significant parameters were selected for both $H_{x \rightarrow y}$ and $H_{y \rightarrow x}$. Surrogate data technique destroys any linear and nonlinear correlations that may exist between the input and output data. Therefore we would expect low coherence values across all times. This is exactly what Fig. 3(e) shows.

Figures 4(a–d) show comparative results based on the STFT for the same simulations as described above with the proposed method. As compared to Figs. 3(a–d), the STFT has a very low resolution both in time and frequency domains. This is an unavoidable and well-documented limitation of the STFT. While these particular simulation examples involve 1024 data points, had there been an even smaller number of data points, the utility of the STFT would

be questionable. Another deficiency that is apparent is the relatively high coherence values even when the signal is contaminated with noise as well as when the system is nonlinear. The third row of Table 1 provides mean TVCF values via the STFT for all four cases considered. As compared to the second row of Table 1, coherence values are significantly higher with the two aforementioned cases, which should have resulted in low coherence values.

We have also compared the proposed approach to the multiple windows using Slepian sequences approach.¹¹ The results are slightly better than with the STFT, but a similar resolution limitation as with the STFT remains with the multiple windows using Slepian sequences method.

In order to compare the performance of our method with the Recursive Least Squares approach (RLS), we show the corresponding results of the RLS in Figs. 5(a–d). The fourth row of Table 1 shows the mean coherence values for Figs. 5(a–d). The model order for the RLS was based on the minimum description length followed by the coefficient estimates using the RLS, and the subsequent calculation of the TVTF and TVCF using Eq. (6) and Eq. (4), respectively. As the figures show, RLS also gives consistently better time-frequency resolution than the STFT while providing similar time-frequency resolution to the proposed method. It is interesting to note that the RLS has an edge effect similar to a high amplitude oscillation at the very low (~ 0 Hz) and high frequencies (~ 0.5 Hz), and they occur only when the system is nonlinear (Figs. 5(c) and (d)). The estimated parameters are unstable during the nonlinear case (not shown). The recursive nature of the RLS, which may lead to over-parameterization and unstable model parameters in nonlinear systems, can be the source of the high amplitude oscillations seen in Figs. 5(c) and (d).

Resolution Comparison

The following simulation example explores time and frequency resolution of the TVCF using comparison between the proposed method and the STFT. The simulation is based on a linear complex frequency modulation signal. For this case, we consider coherences between real and complex portions of the signal. A GWN signal was added to the real portion of the signal and another GWN signal, independent from the first, was added to the complex portion of the signal. In both cases, the resultant signal-to-noise ratio was equal to 20 dB. It is expected that high coherences should be observed only during linear increasing frequencies and time. Figs. 6(a) and (b) are the result of the proposed method and the STFT, respectively. It is apparent that only the proposed method is able to correctly discriminate high coherence values only during the linearly-increasing frequencies and time. Due to the limited time-frequency resolution of the STFT, it is not as accurate as the proposed method in delineating high coherence values

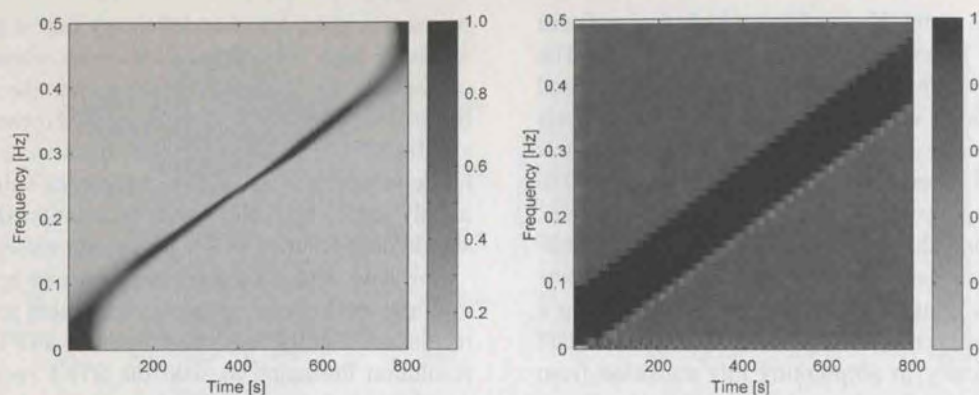


FIGURE 6. Comparison of TVOPS (left panel) and the STFT (right panel) for a complex linear chirp signal.

appearing only at frequencies that are linearly increasing with time.

Application of the Method to Renal System Data

The proposed method is applied to study the nonstationary features of the renal autoregulatory mechanisms and how these features might be different between time-invariant and TV correlation functions for normotensive rats. Renal autoregulation is the process in which fluctuations in renal blood flow caused by fluctuations in blood pressure are minimized. The myogenic mechanism and tubuloglomerular feedback (TGF) are the two mechanisms known to be responsible for renal autoregulation. The myogenic mechanism and TGF are shown to oscillate in the frequency range of 0.1–0.2 Hz and 0.03–0.05 Hz, respectively.^{5–7}

To estimate the TVCF of the renal autoregulatory system, the renal blood flow data were recorded under broadband forced arterial blood pressure fluctuations. The detailed experimental data collection procedures can be found in reference.⁷

Data analysis is based on 4 recordings from normotensive rats. Each of the experimental data records used for analysis was 256 s long, with a sampling rate of one sample per second, after digital low-pass filtering to avoid aliasing. Each data record, containing 256 data points, was subjected to second-degree polynomial trend removal (which included demeaning) and was normalized to unit variance. Representative time series of the blood pressure (top panel) and blood flow (bottom panel) are shown in Fig. 7.

The estimated TVCFs for the 4 normotensive rats are shown in the left panels of Fig. 8. The top right panels of Fig. 8 show a portion of the TV coherence values of the left panels from 0.03 to 0.05 Hz. These curves represent the frequency range where the TGF mechanism is known to operate and is shown for the readers' convenience. The bottom-most curves represent 0.03 Hz and the top-most curves represent 0.05 Hz. The bottom right panels represent the time-invariant coherence functions, shown for convenient comparison to the TVCFs.

For the myogenic mechanism (0.1–0.2 Hz), high coherence values are observed for all times for all four rats. Time invariant coherence functions also show high coherence

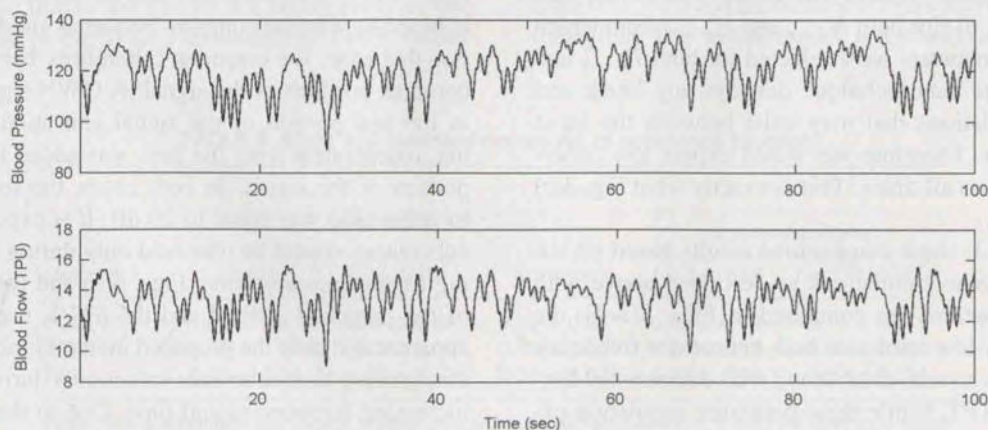
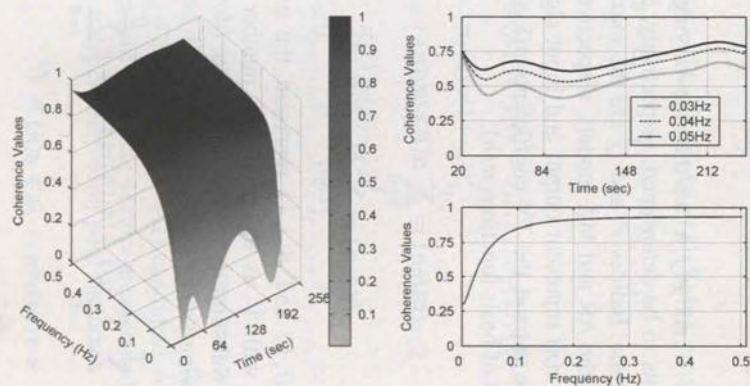
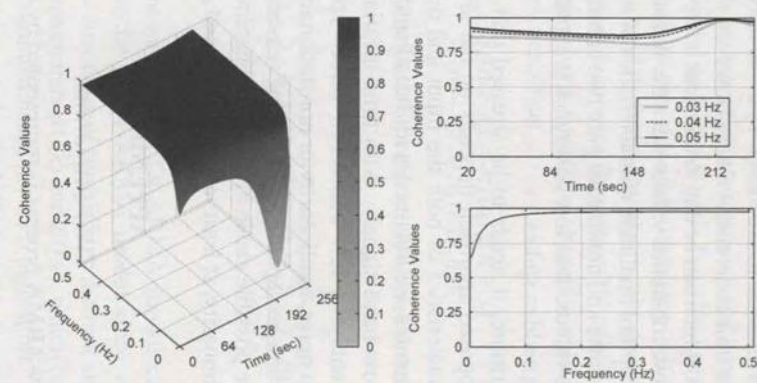


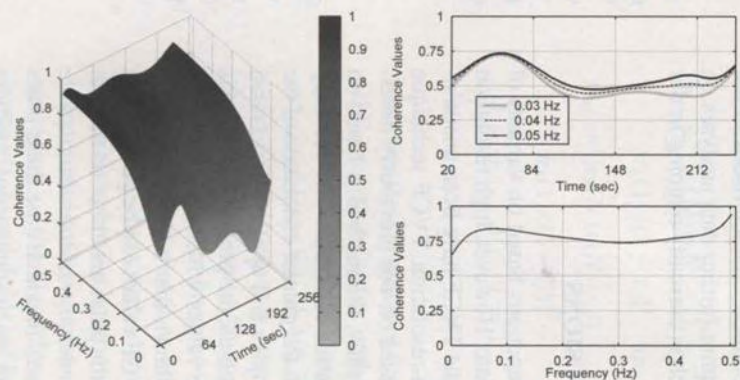
FIGURE 7. Representative blood pressure (top panel) and blood flow (bottom panel) data.



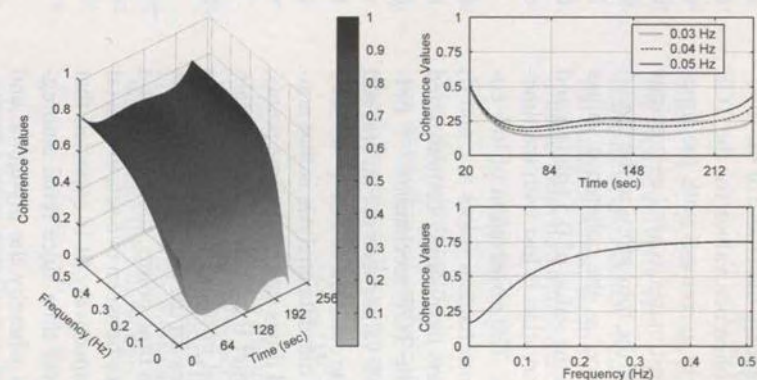
(a)



(b)



(c)



(d)

FIGURE 8. (a)–(d) TVCFs on renal blood flow and pressure data obtained from 4 rats. Top right panels show a portion of the TV coherence values of the left panels from 0.03 to 0.05 Hz. Bottom-right panels represent time-invariant coherence values.

values for all four rats at the myogenic mechanism's frequency range. The TGF, however, shows lower coherence values that are more time-dependent than those of the myogenic mechanism. The low coherence values for the TGF with the TVCF estimate are in agreement with the time-invariant coherence function estimates as well as previous other data analyses.⁵⁻⁷ Two of the four plots, in the region of TGF show time dependence, as the coherence values fluctuate above or lower than the value of 0.5 (plots a and c). Note that this type of observation is lost with the time-invariant coherence functions. The observation of low coherence values for the TGF mechanism (plots a, c and d) is expected, as previous reports have amply demonstrated nonlinear characteristics of the TGF mechanism.^{4,12} Furthermore, fluctuations of TVCF values seen in Fig. 8(a) and 8(c) are all greater than the time constant of TGF (~33 sec). The new insight gained from our data analysis is that nonlinearity does not occur for all times (at certain time points, TV coherence values are greater 0.5), but rather at certain time points. The physiological implication of the increase or decrease of coherence values for the renal blood pressure and flow data is that at certain time points, there is either a high or low degree of coherence between two sets of data (at certain frequency ranges), respectively. It is expected that coherence values fluctuate over time since renal autoregulation is a dynamic process whereby the myogenic and TGF mechanisms work in concert to maintain steady renal blood flow while blood pressure varies over a wide pressure range. For a complete understanding of the physiological basis of nonstationary and nonlinear characteristics of the TGF mechanism, we will require further data analyses on more experimental data, which is currently ongoing in our laboratory.

CONCLUSIONS

Time-varying coherence functions based on variants of the STFT are simple to calculate. However, high resolution and meaningful estimates of the TVCF have been unattainable. A simple and yet high-resolution TVCF technique has been introduced and is based on our previously developed TVTF estimate. Specifically, the method is based on multiplication of transfer function estimates. The accuracy of the TVCF, thus, depends on the precise estimation of the TVTF. Both simulation examples and application to renal data have shown that in most cases, the proposed method is reliable and yields coherence values within the bounds of 0 and 1. However, we have shown that with the proposed approach, in certain cases, TVCF values can be greater than 1. This scenario occurs when the poles are either on the unit circle periphery or as they undergo transition from stable to unstable poles (or vice versa), in which case these poles will lie on the unit circle for an instantaneous moment of time. Poles on the unit circle will result in coherence values greater than 1. In certain biological data, the afore-

mentioned scenario may occur. For example, signals that bifurcate from stable to unstable dynamics or bifurcation from deterministic to stochastic systems may all result in larger than unit coherence values. However, sudden spikes in the data, which can be due to transient noise glitches, will result in low coherence values since the linear TVTF is not suited to capture nonlinear characteristics of sudden spikes. Note that noise and nonlinearity are two contributors to low coherence values, thus, low coherence is expected with data exhibiting sudden spikes.

Furthermore, it needs to be stressed that the accuracy of the proposed approach depends on the level of broadband characteristics of both the input and output signals; better estimates are obtained with broadband signals than with narrow band signals. With time-invariant coherence function analysis, low coherence values are usually attributed to noise, nonlinearity or nonstationarity. However, with a technique capable of estimating reasonably accurate TVCF, the possible cause of the low coherence values due to nonstationarity, at least, can be eliminated.

APPENDIX

TVOPS Algorithm

The TV-ARMA process is represented by the following equation:

$$y(n) = \sum_{i=1}^P a(i, n)y(n-i) + \sum_{j=0}^Q b(j, n)x(n-j) + e(n) \quad (\text{A.1})$$

where $a(i, n)$ and $b(j, n)$ are the time-varying AR and MA coefficients to be determined, respectively, and are functions of time. Indices P and Q are the maximum model orders of the AR and MA models, respectively. Variables $y(n)$ and $x(n)$ represent output and input signals, respectively. We expand the TV coefficients $a(i, n)$ and $b(j, n)$ onto a set of basis functions $\pi(n)$:

$$\begin{aligned} a(i, n) &= \sum_{k=0}^V \alpha(i, k)\pi_k(n) \\ b(j, n) &= \sum_{k=0}^V \beta(j, k)\pi_k(n) \end{aligned} \quad (\text{A.2})$$

where $\alpha(i, k)$ and $\beta(j, k)$ represent the expansion parameters with V as the maximum number of basis sequences. Substituting Eq. (A.2) into Eq. (A.1), we obtain the following:

$$\begin{aligned} y(n) &= \sum_{i=1}^P \sum_{k=0}^V \alpha(i, k)\pi_k(n)y(n-i) + \sum_{j=0}^Q \sum_{k=0}^V \beta(j, k) \\ &\quad \times \pi_k(n)x(n-j) + e(n) \end{aligned} \quad (\text{A.3})$$

The next step is to select proper basis functions so that TV coefficients can be estimated. We have experimented

with three different types of basis functions: Legendre polynomial, discrete prolate spheroidal sequence (DPSS), and Walsh. Our experience has shown that different basis functions show their own unique tractability and accuracy. Legendre polynomial and DPSS basis functions perform well if the coefficients are smoothly changing with time, for example, sinusoidal. Walsh functions, on the other hand, behave well for piece-wise stationary TV coefficients.

Once proper basis functions, $\pi(n)$, have been chosen, we create new variables:

$$\begin{aligned} y_k(n-i) &= \pi_k(n)y(n-i) \\ x_k(n-j) &= \pi_k(n)x(n-j) \end{aligned} \quad (\text{A.4})$$

Substituting Eq. (A.4) into Eq. (A.3) results in the following expression:

$$\begin{aligned} y(n) &= \sum_{i=1}^P \sum_{k=0}^V \alpha(i, k) y_k(n-i) + \sum_{j=0}^Q \sum_{k=0}^V \beta(j, k) x_k \\ &\quad \times (n-j) + e(n) \end{aligned} \quad (\text{A.5})$$

Eq. (A.5) shows that the TV-ARMA model can now be considered to be a TIV-ARMA model since $\alpha(i, k)$ and $\beta(j, k)$ are not functions of time. Thus, the task simplifies to solving for parameters $\alpha(i, k)$ and $\beta(j, k)$, which can be more effectively estimated using the OPS algorithm.⁹

The algorithm of the TVOPS follows the similar two-step procedure of OPS. There are two main differences, however. The first is that we arrange the pool of candidate vectors in the following matrix form:

$$\begin{aligned} \mathbf{M} &= (\mathbf{Y}_0(n-1), \dots, \mathbf{Y}_V(n-1), \mathbf{X}_0(n), \dots, \mathbf{X}_V(n), \\ &\quad \mathbf{Y}_0(n-2), \dots, \mathbf{Y}_V(n-2), \dots) \end{aligned} \quad (\text{A.6})$$

where

$$\mathbf{Y}_k(n-i) = [\pi_k(N)y(N-i), \dots, \pi_k(2)y(2-i), \pi_k(1)y(1-i)]^T$$

$$\mathbf{X}_k(n-j) = [\pi_k(N)x(N-j), \dots, \pi_k(2)x(2-j), \pi_k(1)x(1-j)]^T$$

$$k = 0, \dots, V; \quad i = 1, \dots, P; \quad j = 0, \dots, Q$$

Note that bold and unbold letters represent vectors (or matrices) and scalars, respectively. Among the pool of $P \times (V+1) + (Q+1) \times (V+1)$ candidate vectors, linearly independent candidate vectors are selected to form a new linearly independent vector pool such that:

$$\mathbf{W} = (w_1, w_2, \dots, w_S)$$

where S is the number of linearly-independent candidate vectors.

With the new candidate pool of linearly-independent vectors, least-squares analysis is performed:

$$\mathbf{Y} = \mathbf{W}\Theta + \mathbf{E} \quad (\text{A.7})$$

where $\Theta = [\theta_1, \theta_2, \dots, \theta_S]^T$, $\mathbf{Y}$ is the signal vector and $\mathbf{E}$ is the prediction error vector. In Eq. (A.7), θ_i is the coefficient estimate of the ARMA model. The objective is to minimize the equation error, $\mathbf{E}$, in the least-squares sense using the criterion function defined as follows:

$$J_N(\Theta) = [\mathbf{Y} - \mathbf{W}\Theta]^T [\mathbf{Y} - \mathbf{W}\Theta] \quad (\text{A.8})$$

The criterion function in Eq. (A.8) is quadratic in Θ , and can be minimized analytically with respect to Θ , yielding the following well-known equation:

$$\hat{\Theta} = [\mathbf{W}^T \mathbf{W}]^{-1} \mathbf{W}^T \mathbf{Y} \quad (\text{A.9})$$

The next stage of the algorithm involves further pruning of insignificant linearly-independent candidate vectors obtained from the first stage of the algorithm (Eqs. (A.4–A.6)). To determine which of the candidate vectors are significant, we calculate the following:

$$C_m = \frac{1}{N} \hat{\theta}_m^2 \mathbf{w}_m^T \mathbf{w}_m \quad m = 1 \sim S \quad (\text{A.10})$$

where S represents the number of linearly-independent candidate vectors and $\hat{\theta}_m$ represents the coefficient obtained from Eq. (A.9). Note that the vector $\mathbf{w}_m$ is calculated using Eq. (A.11):

$$\mathbf{w}_m = [\pi_k(N)y(N-i), \dots, \pi_k(2)y(2-i), \pi_k(1)y(1-i)]^T \quad \text{or}$$

$$\mathbf{w}_m = [\pi_k(N)x(N-j), \dots, \pi_k(2)x(2-j), \pi_k(1)x(1-j)]^T$$

$$k = 0, \dots, V; \quad i = 1, \dots, P; \quad j = 0, \dots, Q;$$

$$n = 1, \dots, N; \quad m = 1, \dots, S \quad (\text{A.11})$$

Note that the operation of Eq. (A.10) involves the adding of all C_m together for $\mathbf{w}_m$ with the same $y(n-i)$ or $x(n-j)$ but with different π_k . A magnitude value of each C_m , as estimated from Eq. (A.10), is then arranged in descending order. We only retain $\mathbf{w}_m$ terms that significantly reduce the estimation residuals. An approach that can be adopted to determine the significance of C_m terms is to calculate $(C_m - C_{m+1})/C_m$ and plot it as a function of m . The significant term can be characterized by the first maximum value in the plot. This operation has the added benefit of also discarding insignificant basis sequences, π_k , at the same time. The final procedure of the algorithm is to estimate ARMA model terms $\alpha(i, k)$ and $\beta(j, k)$ of Eq. (A.3) using the least-squares method and the calculation of TV coefficients $a(i, n)$ and $b(j, n)$ using Eq. (A.2).

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ATTACHMENT 1A

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 510 2#\$aEngineering index annual (1968) \$x0360-8557.
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ATTACHMENT 1B

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LIBRARY OF CONGRESS AUTHORITIES

[Help](#)[New Search](#)[Search History](#)[Headings List](#)[Start Over](#)[Previous](#)[Next](#)[MARC Display](#)[Labelled Display](#)**LC control no.:** sh2007102015**LCCN Permalink:** <https://lcn.loc.gov/sh2007102015>**HEADING:** Biomedical engineering Periodicals

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Washington, DC 20540**Library of Congress Authorities**URL: <http://authorities.loc.gov/>**Library of Congress Online Catalog**URL: <https://catalog.loc.gov/>**Questions, comments, error reports:** [Contact Us](#)

ATTACHMENT 1C

Bibliographic Record - OCLC Number: 8878354

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210 0 IEEE eng. med. biol. mag.

222 0 IEEE engineering in medicine and biology magazine

245 0 0 IEEE engineering in medicine and biology magazine : \$b the quarterly magazine of the Engineering i
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246 3 Institute of Electrical and Electronics Engineers engineering in medicine and biology magazine

246 3 0 I.E.E.E. engineering in medicine and biology magazine

246 3 0 E.M.B. magazine

246 1 3 EMB magazine

260 [New York, NY] : \$b The Society, \$c [©1982-

300 volumes : \$b illustrations ; \$c 28 cm

310 Bimonthly, \$b 1995-2010

321 Quarterly, \$b 1982-1994

336 text \$b txt \$2 rdacontent

337 unmediated \$b n \$2 rdamedia

338 volume \$b nc \$2 rdacarrier

362 0 Vol. 1, no. 2 (June 1982)-

362 1 Ceased with vol. 29, no. 3 (May/June 2010).

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710 2 IEEE Engineering in Medicine and Biology Society.

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 260 ##\$aNew York, N.Y. : \$bInstitute of Electrical and Electronics Engineers, \$cc1964-
 300 ##\$av. : \$bill., ports. ; \$c28 cm.
 310 ##\$aMonthly \$b<, Jan. 1979- >
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 321 ##\$aQuarterly, \$b1964-<Jan. 1969>
 362 0#\$aVol. BME-11, no. 1 & 2 (Jan./Apr. 1964)-
 510 2#\$aChemical abstracts \$x0009-2258 \$b1864-1982
 530 ##\$aAlso issued online.
 550 ##\$aVols. for 1964-Oct. 1964 issued by the Bio-medical Engineering Group of the IEEE;
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680 __ |i Here are entered works on the periodicals of the world and, with appropriate subdivisions, works on special aspects or sections of periodicals. Works on periodicals in a specific language, or in a specific country or larger area, are entered under the adjectival form of the language or area, e.g. |a Arabic periodicals; Canadian periodicals.

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ATTACHMENT 2E

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ATTACHMENT 3A

Third International Conference on Independent Component Analysis and Signal Separation : San Diego, California, December 9 - 13, 2001 (Englisch)

[International Conference on Independent Component Analysis and Signal Separation](#)

2001

- Konferenzband / Datenträger

Mehr Angaben zu diesem Treffer

- **Titel:**

Third International Conference on Independent Component Analysis and Signal Separation : San Diego, California, December 9 - 13, 2001

- **Beteiligte:**

[Lee, Te-Won / International Conference on Independent Component Analysis and Signal Separation](#)

- **Kongress:**

International Conference on Independent Component Analysis and Signal Separation ; 3 ; 2001 ; San Diego, Calif.

ICA 2001 ; 3 ; 2001 ; San Diego, Calif.

- **Erscheinungsort:**

San Diego, Calif.

- **Erscheinungsdatum:**

2001

- **Format / Umfang:**

1 CD-ROM

- **Anmerkungen:**

Parallel als Buch-Ausg. erschienen

- **Medientyp:**

Konferenzband

- **Format:**

Datenträger

- **Sprache:**

Englisch

- **Datenquelle:**

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TIB – Leibniz Information Centre for Technology and Natural Sciences and University Library
(Hanover, Germany)

ATTACHMENT 3B

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008	Date Entered on File	'030404'
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	Date2/Ending Date of Publication	' '
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	Nature of Contents Code	'b '
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	Conference Publication	'1' - Conference publication
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337	unmediated \$b n \$2 rdamedia	
338	volume \$b nc \$2 rdacarrier	

504 Includes bibliographical references.
650 0 Signal processing **\$x** Digital techniques **\$v** Congresses.
650 0 Signal processing systems **\$v** Congresses.
650 0 Multivariate analysis **\$v** Congresses.
650 0 Neural networks (Computer science) **\$v** Congresses.
650 6 Traitement du signal **\$x** Techniques numériques **\$v** Congrès.
650 6 Analyse multivariée **\$v** Congrès.
650 6 Réseaux neuronaux (Informatique) **\$v** Congrès.
650 7 Multivariate analysis. **\$2** fast **\$0** (OCoLC)fst01029105
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655 7 Conference papers and proceedings. **\$2** fast **\$0** (OCoLC)fst01423772
700 1 Lee, Te-Won.
740 0 Third International Conference on Independent Component Analysis and Signal Separation, San Diego, California, December 9-13, 2001.
856 4 **\$u** <http://ica2001.ucsd.edu/> **\$z** 3rd International Conference on Independent Component Analysis and Signal Separation
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150 __ |a Signal processing |x Digital techniques |v Congresses

667 __ |a Record generated for validation purposes.

670 __ |a Work cat.: ICSP' 02, 2002

906 __ |t 8888 |u te00 |v 0

953 __ |a te00

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Washington, DC 20540**Library of Congress Authorities**URL: <http://authorities.loc.gov/>**Library of Congress Online Catalog**URL: <https://catalog.loc.gov/>**Questions, comments, error reports:** [Contact Us](#)

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670 __ |a Work cat.: Advances in data analysis and classification, c2001

906 __ |t 8888 |u te00 |v 0

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005 20110729160555.0

008 080305|| anannbabn |n ana

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035 __ |a (DLC)sh2008108385

040 __ |a DLC |b eng |c DLC

150 __ |a Neural networks (Computer science) |v Congresses

667 __ |a Record generated for validation purposes.

670 __ |a Work cat.: Conference proceedings, 1st International IEEE EMBS Conference on Neural Engineering, 20-22 March 2003, Capri Island, Italy, c2003

906 __ |t 8888 |u te00 |v 0

953 __ |a te00

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MARC Bibliographic Record

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245	10	\$a International journal of signal processing.
246	13	\$a IJSP
260		\$a [Place of publication not identified] : \$b World Academy of Science, Engineering and Technology
310		\$a Quarterly

336		\$atext\$btxt\$2rdacontent
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362	1_	\$aBegan with: Vol. 1, no. 1 (winter 2005).
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588		\$aDescription based on: Vol. 1, no. 1 (winter 2005); title from journal home page (publisher's Web site, viewed Feb. 18, 2010).
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MMS IDs

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667 __ |a Record generated for validation purposes.

670 __ |a Work cat.: Signal processing,

906 __ |t 8888 |u tc00 |v 0

953 __ |a tc00

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ATTACHMENT 4C

Bibliographic Record - OCLC Number: 321350076

LDR	Record Status	'c' - Corrected or revised
	Type of Record	'a' - Language material
	Bibliographic Level	's' - Serial
	Type of Control	' ' - No specified type of control
	Encoding Level	' ' - Full level
	Descriptive Cataloging Form	'a' - AACR2
001	321350076	
005	20240429191240.0	
008	Date Entered on File	'060412'
	Type of Date/Publication Status	'c' - Continuing resource currently published
	Date1/Beginning Date of Publication	'2004'
	Date2/Ending Date of Publication	'9999'
	Place of Publication, Production, or Execution Code	'xx ' - No place, unknown, or undetermined
	Frequency	'q' - Quarterly
	Regularity	'r' - Regular
	Type of Continuing Resource	'p' - Periodical
	Form of Original Item	' ' - None of the following
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	Nature of Entire Work	' ' - No specified nature of entire work
	Nature of Contents	' '
	Government Publication	' ' - Not a government publication
	Conference Publication	'0' - Not a conference publication
	Original Alphabet or Script of Title	'a' - Basic Roman
	Entry Convention	'0' - Successive entry
	Language Code	'eng' - English
	Modified Record	' ' - Record is not modified
	Cataloging Source Code	'c' - Cooperative cataloging program
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	Type of Computer File	'd' - Document
	Government Publication	' ' - Not a government publication
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130 0 International journal of signal processing (Online)

245 1 0 International journal of signal processing.

246 1 3 IJSP

260 [Place of publication not identified] : \$b World Academy of Science, Engineering and Technology

310 Quarterly

336 text \$b txt \$2 rdacontent

337 computer \$b c \$2 rdamedia

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362 1 Began with: Vol. 1, no. 1 (winter 2005).

588 Description based on: Vol. 1, no. 1 (winter 2005); title from journal home page (publisher's Web site, viewed Feb. 18, 2010).

588 Latest issue consulted: Vol. 6, no. 2 (spring 2010) (publisher's Web site, viewed Feb. 18, 2010).

650 0 Signal processing \$v Periodicals.

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655 7 Periodicals. \$2 fast \$0 (OCoLC)fst01411641

710 2 World Academy of Science, Engineering and Technology.

776 0 8 \$i Print version: \$t International journal of signal processing \$x 1304-4494

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 222 #0\$aAnnals of biomedical engineering
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 300 ##\$av. \$bill.
 362 0#\$aVol. 1 (Sept. 1972)-
 500 ##\$aJournal of the Biomedical Engineering Society.
 530 ##\$aAlso available online.
 599 11\$aSelected volumes/issues transferred from the Engineering Societies Library, January
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	Date2/Ending Date of Publication	'9999'
	Place of Publication, Production, or Execution Code	'nyu' - New York
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	Form of Original Item	' ' - None of the following
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	Government Publication	' ' - Not a government publication
	Conference Publication	'0' - Not a conference publication
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 650 1 7 Biomedische techniek. **\$2** gtt
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 246 18\$aAJP: \$pregulatory, integrative and comparative physiology
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 500 ##\$aPrint issues ceased with v. 301, no. 6 (2011).
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 510 0#\$91 \$aPubMed \$bv278n1, Jan. 2000-
 510 1#\$aIndex medicus
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 530 ##\$aAlso issued online.
 580 ##\$aAlso issued as a section of the consolidated version of The American journal of
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 650 22\$aHomeostasis \$xphysiology
 650 22\$aPhysiology, Comparative
 655 #2\$aPeriodical
 710 2#\$aAmerican Physiological Society (1887-)
 856 4#\$uhttps://journals.physiology.org/journal/ajpregu

911 ##\$aElectronic only, print ceased 2011. Confirmed 20120224
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999 ##\$aAUTH
035 ##\$a(OCOLC)03022253

ATTACHMENT 6B

Physiological Phenomena MeSH Descriptor Data 2025

Details	Qualifiers	MeSH Tree Structures	Concepts
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MeSH Heading

Physiological Phenomena

Tree Number(s)

G07

Unique ID

D010829

RDF Unique Identifier

<http://id.nlm.nih.gov/mesh/D010829>

Annotation

general or unspecified; prefer specifics; differentiate from PHYSIOLOGY, the specialty or discipline

Scope Note

The functions and properties of living organisms, including both the physical and chemical factors and processes, supporting life in single- or multi-cell organisms from their origin through the progression of life.

Entry Term(s)

- Physiological Concepts
- Physiological Phenomenon
- Physiological Process
- Physiological Processes

Public MeSH Note

2009; see PHYSIOLOGICAL PROCESSES 1998-2008; for PHYSIOLOGICAL PROCESSES see PHYSIOLOGICAL PROCESSES 2009-2016

History Note

2009 (1975)

Date Established

1998/01/01

Date of Entry

1999/01/01

Revision Date

2016/09/28

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ATTACHMENT 6C

Homeostasis MeSH Descriptor Data 2025

Details	Qualifiers	MeSH Tree Structures	Concepts
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MeSH Heading

Homeostasis

Tree Number(s)

G07.410

Unique ID

D006706

RDF Unique Identifier

http://id.nlm.nih.gov/mesh/D006706

Scope Note

The processes whereby the internal environment of an organism tends to remain balanced and stable.

Entry Term(s)

Autoregulation

NLM Classification

QT 120

See Also

Neuroimmunomodulation

Date Established

1966/01/01

Date of Entry

1999/01/01

Revision Date

2016/06/17

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ATTACHMENT 6D

Physiology, Comparative MeSH Descriptor Data 2025

Details	Qualifiers	MeSH Tree Structures	Concepts
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MeSH Heading

Physiology, Comparative

Tree Number(s)

H01.158.782.688

Unique ID

D010828

RDF Unique Identifier

<http://id.nlm.nih.gov/mesh/D010828>

Annotation

the discipline (education, history, etc) only; for comparative physiological studies, use the qualifier/ **physiol** with specific anatomical term, process or organism + the Publication Type **COMPARATIVE STUDY**

Scope Note

The biological science concerned with similarities or differences in the life-supporting functions and processes of different species.

Entry Version

PHYSIOL COMPARATIVE

Entry Term(s)

Comparative Physiology

Date Established

1966/01/01

Date of Entry

1999/01/01

Revision Date

2009/07/06

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Accessibility
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ATTACHMENT 6E

Bibliographic Record - OCLC Number: 3022253

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	Bibliographic Level	's' - Serial
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008	Date Entered on File	'770607'
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	Date1/Beginning Date of Publication	'1977'
	Date2/Ending Date of Publication	'2011'
	Place of Publication, Production, or Execution Code	'mdu' - Maryland
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