

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

VOLKSWAGEN GROUP OF AMERICA, INC.,
Petitioner,

v.

LONGHORN AUTOMOTIVE GROUP LLC,
Patent Owner.

IPR2025-01064
U.S. Patent 8,265,353

Declaration of Shauna L. Wiest Regarding *Kachelrieß*

I, Shauna L. Wiest, state and declare as follows:

I. Introduction

1. I have prepared this Declaration in connection with the Petition for *Inter Partes* Review of U.S. Patent No. 8,265,353, which I understand will be filed concurrently with this Declaration.

2. I am currently a Senior Research Analyst with Finnegan, Henderson, Farabow, Garrett & Dunner, LLP located at 3300 Hillview Avenue, Palo Alto, CA 94304.

3. I am over eighteen years of age, and I am competent to make this Declaration. I make this Declaration based upon my own personal knowledge, and my professional knowledge of library science practices.

4. I earned a Master of Science in Library Science degree from the University of North Carolina at Chapel Hill in 1999, and a Bachelor of Arts in Political Science degree from the University of California at San Diego in 1989. I have worked as a law librarian for twenty years. I have been employed at Finnegan, Henderson, Farabow, Garrett & Dunner, LLP since 2021. Before that, from 2000-2015, I was employed as a Law Librarian at Stoel Rives LLP, and from 2015-2016, I was employed as a Competitive Intelligence Specialist for Nossaman LLP. Additionally, as a graduate student at the University of North Carolina at Chapel Hill, I served as an intern at the Environmental

Protection Agency at Research Triangle Park (“EPA-RTP”) where one of my rotations included original cataloging for EPA technical documents, state agency reports and documents, international organization documents, dissertations, and, on occasion, monographs. In this role, I accessed OCLC, MARC records, and the EPA National Library Catalog daily.

II. Standard Library Practice for Receiving, Cataloging, and Making Materials, including Serial Publications, Publicly Available and Accessible

5. I have knowledge of and experience with standard library practices regarding the receipt, cataloging, shelving, and making materials, including serial publications, available and accessible to the public. I have knowledge of and experience with the Machine-Readable Cataloging (MARC) system, an industry-wide standard that libraries use to catalog materials.

6. Based on standard library practice, when a library receives an item, the cataloguer or cataloguer’s assistant will examine the item and stamp and/or affix a label to the item with the library name and/or barcode with the date it was received. Next, the library will catalog the item within a few days of receiving it. As a general practice, cataloguing is centralized and performed by a cataloguing department within a library or university setting.

7. Normally, after an item is cataloged, the public may access the item by searching a library catalog, browsing the library shelves, and/or

requesting the item from the library. Standard library practice is to make the item available to the public within several days of cataloging it. If an item requires original cataloging, the item will be made available to the public up to and including one week from the date of receipt.

III. Ownership and Date-Stamp

8. Libraries have different policies on whether or not to date stamp publications. It is becoming increasingly common for libraries to no longer date stamp the publications they receive. In the past, it was standard practice to affix an ownership stamp somewhere within the publication, usually on the cover page, verso of the cover page, or a designated page within the publication. The timing of when an ownership stamp is entered on the monograph or periodical can vary from one library to another. It could occur when the item is received in acquisitions after shipment to the library, or at the time of cataloging. Therefore, it is possible for there to be instances when the date of receipt precedes the cataloging date or vice versa.

IV. MARC Records

9. The MARC system was developed during the 1960s to standardize bibliographic catalog records so they could be read by computers and shared among libraries. By the mid-1970s, MARC had become the international standard for cataloging bibliographic materials and is still used today. Many libraries

provide public access to their MARC records via their electronic cataloging systems at the library. In a MARC record, each field provides specific information about the cataloged item, including how materials are held and when they were made available to the public.

10. The MARC record system uses a specific three-digit numeric code (“field tags”) (from 001-999) to identify each field in a catalog record. For example, field tag 008 provides the six-digit date an item was catalogued (*Date entered on file*). The first six characters of field tag 008 are always in the “**YYMMDD**” format. Descriptions and definitions of all of the character positions of field tag 008 are outlined here:

<https://www.loc.gov/marc/bibliographic/bd008a.html>.

11. As is relevant to this Declaration, MARC field tag 022 sets forth the International Standard Serial Number (“ISSN”), a unique identification assigned to every serial publication. MARC field tag 245 sets forth the title information (which includes the title, other title information, and the statement of responsibility). MARC field tag 362 sets forth the dates of publication and/or sequential date designation for a work.

V. Cataloguing Treatment of Serials

12. A serial publication, also known as a “journal,” “periodical,” “newspaper,” or “magazine,” is a resource that is issued in successive parts and

has no predetermined conclusion. These successive parts are commonly referred to as “issues,” and each issue is usually chronologically numbered, bears a unique date, and is received on an expected, ongoing, routine basis. The presence of enumeration, years of coverage, regular receipt, and/or other chronological information, also indicates a serial publication.

13. There are differences between cataloging finite resources (books/monographs) and continuing resources (serials). For serials, the catalog record provides information about the serial, including the first or earliest available issue available. It also provides information as to holdings – the breadth of volumes and issues received, checked in, and held by a library, including the public availability of those holdings. In serials cataloging, there are identifying characteristics unique to serials that are slightly different from monographs (books). The issue date for a serial publication, for example, generally appears on the cover (front or back), the masthead page, the title page (if any), the table of contents page(s), or on the pages of the individual articles contained within the issue. More information regarding the unique aspects of cataloguing serials can be found at this link:

<https://www.loc.gov/aba/pcc/conser/scctppt/Basic-2014/Basic-Trainee-Mannual.pdf>.

VI. Public Availability and Accessibility of *Kachelrieß*

14. Section VI of this Declaration relates to the date of receipt and public availability/accessibility for the following reference: Kachelrieß M, Sennst DA, Maxlmoser W, Kalender WA. “*Kymogram detection and kymogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart.*” Medical Physics 2002 July; Vol. 29 (No. 7), Pages 1489-1503 (“*Kachelrieß*”). I understand that *Kachelrieß* has been submitted as **Exhibit Ex-1023** in this proceeding. This reference is appended to my Declaration as **Appendix A**.

15. As detailed below, I have reviewed the print *Kachelrieß* reference, which was supplied to me by Wisconsin Tech Search (a service of the University of Wisconsin - Madison) on May 15, 2025, the University of Wisconsin Library public holdings information and MARC record for *Kachelrieß* to determine the date of its public availability and accessibility.

16. **Appendix A** to this Declaration is a true and accurate copy of the cover, front matter, table of contents, and date stamp for the print issue of Medical Physics containing *Kachelrieß* held by the Health Sciences Library at the University of Wisconsin. **Appendix A** includes pages 1489-1503, which comprise the print *Kachelrieß* reference. **Appendix A** includes a date-stamp on PDF page 1 indicating that the issue of Medical Physics containing *Kachelrieß* was received by

the University of Wisconsin Health Sciences Library on July 19, 2002. **Appendix A** also sets forth the ISSN for the print journal as 0094-2405 on PDF pages 2 and 3.

17. **Appendix B** to this Declaration is a true and accurate copy of the University of Wisconsin Library public catalog record for its copy of Medical Physics containing *Kachelrieß*, which was downloaded from <https://search.library.wisc.edu/catalog/999483150302121> on May 28, 2025.

18. The University of Wisconsin Library public catalog record (**Appendix B**) sets forth the publication and holding details for its copy of Medical Physics containing *Kachelrieß*. The public catalog record indicates that the Ebling Library holds v. 42 (2015) through v. 43 (2016) in the Stacks at call number Q 7M4613 P5, and that the Middleton Shelving Facility holds print Volume 1 (1974) through Volume 41 (2014) of the print serial publication Medical Physics. **Appendix B** also sets forth the ISSN number as 0094-2405.

19. **Appendix C** to this Declaration is a true and accurate copy of the University of Wisconsin Library MARC record for its holdings of the print journal Medical Physics, which was downloaded from <https://search.library.wisc.edu/catalog/999483150302121> (Click on “Library Staff Details” and then “Staff View”) on May 28, 2025.

20. **Appendix C** confirms the fixed data elements of MARC field tag 008 as 741029c19749999nyubr1p. As discussed above, the first six characters “741029” are in typical “**YYMMDD**” format and indicate that the print journal Medical Physics was first catalogued by the University of Wisconsin - Madison Library on October 29, 1974, and that the journal began publication in 1974 and is a continuing resource currently published with no end date noted.

21. The University of Wisconsin - Madison Library MARC record (**Appendix C**) field tag 245 sets forth the title as Medical Physics. MARC field tag 022 sets forth the ISSN number for Medical Physics as 0094-2405, which matches the ISSN in **Appendix A** and **Appendix B**. MARC field tag 362 denotes the dates of publication and/or sequential date designation for Medical Physics as Vol. 1, no. 1 (1974)-.

22. Based on the information set forth in **Appendices A, B, and C** attached to this Declaration, standard library practices, and my experience as a librarian, the issue of Medical Physics containing *Kachelrieß* was received by the University of Wisconsin Health Sciences Library staff on July 19, 2002.

23. Accordingly, the issue of Medical Physics containing *Kachelrieß* would have been checked-in and catalogued by the University of Wisconsin Health Sciences Library within a few days of July 19, 2002, and would have subsequently been made available to the public within a few days of being checked-in and

catalogued. Members of the interested public could have accessed the issue of Medical Physics containing *Kachelrieß* by (i) searching the University of Wisconsin Library catalog; (ii) visiting the Eberling library; or (iii) by asking a Library staff member and requesting the print issue containing *Kachelrieß* available at the Middleton Shelving Facility at Call Q 7M4613 P5 (23-D-6) no later than July 26, 2002.

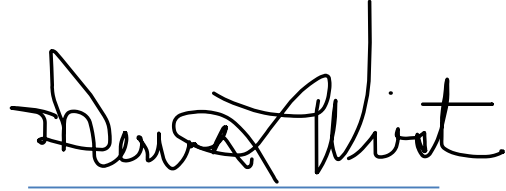
VII. Conclusion

24. In signing this Declaration, I understand it will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I understand I may be subject to cross-examination in this 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.

25. I declare that all statements made herein of my knowledge are true, that all statements made on information and belief are believed to be true, and 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.

Declaration of Shauna L. Wiest

Executed on May 29, 2025.

A handwritten signature in black ink, appearing to read "Shauna L. Wiest", written over a horizontal blue line.

Shauna L. Wiest

HSL

Medical Physics

AVAILABLE ONLINE—See <http://www.medphys.org>

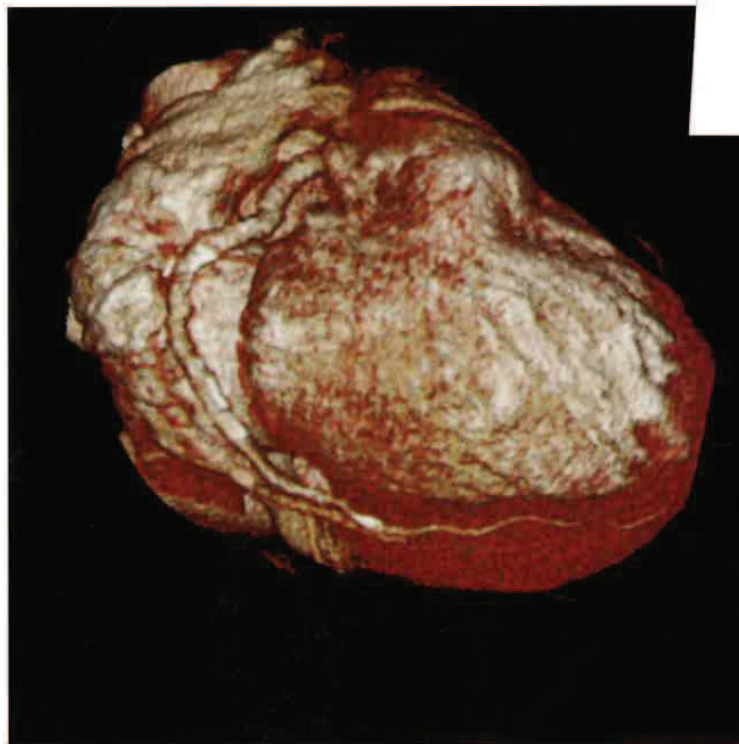
July 2002

Volume 29, Number 7

HEALTH SCIENCES LIBRARY
UNIVERSITY OF WISCONSIN

JUL 19 2002

1305 Linden Drive
Madison, WI 53706



Reconstruction of 12-slice cardiac CT data viewed from anterior/caudal using volume rendering. The coronary arteries are nicely depicted at full length. See "Kymogram detection and kymogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart," pages 1489–1503.

Published by the American Association of Physicists in Medicine (AAPM) with the association of the Canadian Organization of Medical Physicists (COMP) and the Canadian College of Physicists in Medicine (CCPM) through the American Institute of Physics. *Medical Physics* is the official science journal of the AAPM and is an official science journal of COMP/CCPM.



Elected Officers

Robert G. Gould	President
University of California, San Francisco	
Martin Weinhaus	President Elect
Cleveland Clinic Foundation	
Gerald White	Secretary
Colorado Associated in Medical Physics	
Melissa C. Martin	Treasurer
Therapy Physics, Inc.	
Charles W. Coffey II	Chairman of the Board
Vanderbilt Medical Center	

Sal Trofi, Jr.	Executive Director
American Association of Physicists in Medicine	
One Physics Ellipse	
College Park, MD 20740-3846	(301) 209-3350

The American Association of Physicists in Medicine was founded in 1958. Its purposes are to promote the application of physics to medicine and biology, encourage interest and training in medical physics and related fields. The AAPM has established *Medical Physics* as its primary scientific and informational journal. The AAPM is a Member of the American Institute of Physics. AAPM membership information and application forms may be obtained from the Executive Director.

Corporate Affiliates

Acceltronics, Inc.
ADAC Laboratories
Advanced Radiation Measurements, Inc.
AMAC
Bicron Radiation Measurement Products
Biodes Medical Systems
BrainLAB AG
Capintec, Inc.
CNMC Company, Inc.
Computerized Imaging Reference Systems, Inc.
Computerized Medical Systems, Inc.
Computerized Radiation Scanners, Inc.
Eastman Kodak Company
Eberline Instruments
Elekta
Frank Barker Associates, Inc.
Gammex, Inc.
Guidant Corporation
Huestis Medical
IBT, Inc.
ICN Worldwide Dosimetry Services
IMPAC Medical Systems, Inc.
Implant Sciences Corporation
Invision Radiation Measurements
K & S Associates, Inc.
Landauer, Inc.
LAP of America, L.C.
Lone Star Lead Construction
MDS Nordion
MED-TEC, Inc.
Mentor
MGS Research, Inc.
Mick Radio Nuclear Instruments
Multidata Systems International, Corp.
Neutron Products, Inc.
NOMOS Corporation
Nuclear Associates
Nuclear Shielding Supplies & Service
Nucletron Corporation
Nycomed/Amersham
The Phantom Laboratory, Inc.
Prowess Systems / SSGI
Proxima Therapeutics, Inc.
PTW - New York
Radcal Corporation
Radiation Products Design, Inc.
Radiological Imaging Technology, Inc. (R.I.T.)
Radionics, Inc.
RTI Electronics AB
Scanditronix Wellhofer North America
Siemens Medical Systems-OCS
Standard Imaging, Inc.
Sun Nuclear Corporation
Synacor International
Theragenics Corporation
Thomson & Nielsen Electronics, Ltd.
Unfors Instruments
URDC, Inc.
UroMed Corporation
Varian Medical Systems

The AAPM has established the category of Corporate Affiliates for corporations wishing to aid the Association through their participation and membership dues. The AAPM cordially invites interested corporations to make application for Corporate Affiliation. Inquiries should be addressed to the Executive Director.

Medical Physics

ISSN: 0094-2405
CODEN MPHYA6

EDITOR

Colin G. Orton, Wayne State University, School of Medicine, Detroit, MI 48201

DEPUTY EDITOR (IMAGING)

John M. Boone, University of California Davis, Sacramento, CA

DEPUTY EDITOR (THERAPY)

Richard L. Maughan, University of Pennsylvania, Department of Radiation Oncology, Philadelphia, PA 19104

JOURNAL MANAGER

Penny Slattery, AAPM, College Park, MD

FORMER EDITORS

Gail D. Adams, University of Oklahoma (*Emeritus*), Volumes 1-5
Edward Siegel, University of California at San Francisco, Volumes 6-8
Edward L. Chaney, University of North Carolina School of Medicine, Volumes 9-11
Fearghus O'Foghliudha, Duke University (*Emeritus*), Volumes 12-14
John S. Laughlin, Memorial Sloan-Kettering Cancer Center, Volumes 15-23

ASSOCIATE EDITORS

Rodica Alecu (03), Texas Cancer Center—Sherman
Gary T. Barnes (04), University of Alabama—Birmingham
Sam Beddar (04), Case Western Reserve University—Cleveland
John M. Boone (03), University of California Davis—Sacramento
Michael J. Bronskill (02), Sunnybrook Health Science Center—Toronto
Ramesh Chandra (02), New York University Medical Center—New York
Brenda Clark (02), British Columbia Cancer Agency—Vancouver
Ian Cunningham (04), Robarts Research Institute—Ontario
Rupak Das (04), University of Wisconsin—Madison
Joe Deasy (03), Mallinckrodt Institute of Radiology—St. Louis
B. Gino Fallone (02), Cross Cancer Institute/University of Alberta—Edmonton
Aaron Fenster (02), University of Western Ontario—London
David Followill (02), M.D. Anderson Cancer Center—Houston
Maryellen L. Giger (04), University of Chicago—Chicago
Albert Goldstein (02), Wayne State University—Detroit
Christopher Gordon (03), University of California San Francisco—San Francisco
Ellen Grein (02), British Columbia Cancer Agency—Vancouver
Christine Hartmann-Siantar (02), Lawrence Livermore National Lab—Livermore
John D. Hazle (02), M.D. Anderson Cancer Center—Houston
Michael Herman (04), Mayo Clinic—Rochester
Shirish Jani (04), Scripps Clinic & Research Foundation—La Jolla
David Jette (02), The Lawrence H. Lanzl Institute of Medical Physics—Seattle
Willi Kalender (04), University of Erlangen—Germany
Andrew Karellas (04), University of Massachusetts Medical Center—Worcester
Eric E. Klein (02), Mallinckrodt Institute—St. Louis
Chandrasekhar Kota (04), University of Pennsylvania—Philadelphia
Elizabeth Krupinski (02), University of Arizona—Tucson
Chang-Ming Charlie Ma (04), Fox Chase Cancer Center—Philadelphia
Richard L. Maughan (02), University of Pennsylvania—Philadelphia
Ali Meigooni (04), University of Kentucky Medical Center—Lexington
Dimitris Mihailidis (03), Richland Memorial Hospital—Columbia
Eduardo Moros (02), Mallinckrodt Institute of Radiology—St. Louis
Alan Nahum (04), The Royal Marsden Hospital—London
Ravinder Nath (02), Yale University Medical School—New Haven
Azam Niroomand-Rad (03), Georgetown University Medical Center—Washington, DC
Jatinder R. Palta (02), University of Florida—Gainesville
Norbert J. Pelc (02), Stanford University School of Medicine—Stanford
Ervin B. Podgorsak (02), McGill University/Montreal General Hospital—Montreal
Chester Ramsey (03), Thompson Cancer Survival Center—Knoxville
Lawrence E. Reinstein (02), State University of New York at Stony Brook—New York
Mark J. Rivard (03), Tufts University School of Medicine—Boston
David W. O. Rogers (02), National Research Council of Canada—Ottawa
Surendra N. Rustgi (04), Case Western Reserve University—Cleveland
James B. Smathers (02), University of California—Los Angeles
Ge Wang (02), University of Iowa—Iowa City
Mark B. Williams (04), University of Virginia—Charlottesville
Jeffrey Williamson (03), Mallinckrodt Institute of Radiology—St. Louis
Ellen D. Yorke (02), Memorial Sloan-Kettering Cancer Center—New York
Timothy Zhu (04), University of Pennsylvania—Philadelphia

DEPARTMENTS

John R. Cameron, Ph.D. Theses Abstracts (04), University of Wisconsin—Madison
William R. Hendee, Point/Counterpoint Moderator (02), Medical College of Wisconsin—Milwaukee
Andrew Karellas Review Articles (Diagnostic) (04) University of Massachusetts Medical Center—Worcester
Charles Lescrenier, Industry (02), Gammex/RMI—Wauwatosa
Christopher Marshall, Chairman, Journal Business Management Committee (04), New York University Medical Center—New York
Melissa Martin, AAPM Treasurer (02), Therapy Physics, Inc.—Bellflower
Jatinder R. Palta, Review Articles (Therapy) (02), University of Florida—Gainesville
Chester Reft, Books and Publications (03), University of Chicago—Chicago
Carter Schroy, Calendar (02), Grant/Riverside Methodist Hospitals—Columbus

EDITORIAL STAFF

Team Manager: **Doug Parker**; Team Coordinator: **Thomas Thrash**;
Chief Production Editor: **Diane Brzozowski**

MEDICAL PHYSICS publishes articles broadly concerned with the relationship of physics to human biology and medicine. Physics may be applied to any biological system; its role may be theoretical, experimental, or clinical. Review articles, research reports, short technical reports, and letters are acceptable.

Submission of a manuscript indicates that it has not been published previously nor concurrently submitted for publication elsewhere. The manuscript should be accompanied by a statement transferring copyright from the authors (or their employers—whoever holds the copyright) to the American Association of Physicists in Medicine; a suitable form for copyright transfer is available from the Editorial Office at College Park. Detailed information on manuscript submission can be found in the January issue.

Medical Physics

Volume 29, Number 7, July 2002

RADIATION PROTECTION PHYSICS

Point/Counterpoint

A prospective study should be performed to test the hypothesis that an increase in background radiation to residents in the gulf states will increase their longevity

John R. Cameron and Jeffrey Kahn 1511

An in-phantom dosimetry system using pin silicon photodiode radiation sensors for measuring organ doses in x-ray CT and other diagnostic radiology

Takahiko Aoyama, Shuji Koyama, and Chiyo Kawaura 1504

RADIATION THERAPY PHYSICS

Relative biological effectiveness enhancement of a ^{125}I brachytherapy seed with characteristic x rays from its constitutive materials

Richard Taschereau, René Roy, and Jean Pouliot 1397

Implementation of the isocenter-shift technique for smoothing MLC field edge on a 3D treatment planning system

Jinyu Xue, Pengpeng Zhang, Jackie Wu, Zhiheng Wang, and Claudio Sibata 1413

Dose broadening due to target position variability during fractionated breath-held radiation therapy

W. G. O'Dell, M. C. Schell, D. Reynolds, and P. Okunieff 1430

A comparison of physically and radiobiologically based optimization for IMRT

Lois Jones and Peter Hoban 1447

(Continued)

Subscription Prices (2002)	U.S.A. and Poss.	Can., Mex., and Central and So. Amer.	Europe, Asia, Africa, and Oceania [†]
AAPM members		On Membership	
Members of IOMP, AIP, and Affiliated Societies	\$245	\$285	\$310
All others	\$770	\$810	\$835

[†]Includes air freight service.

Back-Number Prices. 2002 Single copies \$75. Prior to 2002 single copies \$110.

Medical Physics (ISSN: 0094-2405) is published monthly by the AAPM through the American Institute of Physics. 2002 subscription rates are: US \$770. POSTMASTER: Send address changes to *Medical Physics*, AIP, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502. Periodicals postage paid at Huntington Station, NY and additional mailing offices. Membership in the American Association of Physicists in Medicine includes \$40.00 from membership dues to be applied towards a subscription to *Medical Physics*.

Subscriptions, renewals, and address changes should be addressed to AIP Circulation and Fulfillment Division (CFD), Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502. Allow at least six weeks advance notice. For address changes please send both old and new addresses and, if possible, include a mailing label from the wrapper of a recent issue.

Digital Object Identifier (DOI): Each archival article published is assigned a unique DOI that serves to identify the article in a digital environment. In print, the DOI appears at the end of each abstract.

Document Delivery: Copies of journal articles can be ordered for online delivery from DocumentStore, AIP's online document delivery service (<http://www.documentstore.org/>).

Advertising rates will be supplied on request. Orders, advertising copy, and offset negatives should be sent to the AIP Manager of Exhibits and Advertising, Richard Kobel.

Copyright © 2002. American Association of Physicists in Medicine. All rights reserved.

Copying: Single copies of individual articles may be made for private use or research. Authorization is given (as indicated by the Item Fee Code for this publication) to copy articles beyond the use permitted by Sections 107 and 108 of the U.S. Copyright Law, provided the copying fee of \$19 per copy per article is paid to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923, USA. Persons desiring to photocopy materials for classroom use should contact the CCC Academic Permissions Service. The Item Fee Code for this publication is 0094-2405/2001 \$19.00.

Authorization does not extend to systematic or multiple reproduction, to copying for promotional purposes, to electronic storage or distribution, or to republication in any form. In all such cases, specific written permission from AIP must be obtained.

Permission for Other Use: Permission is granted to quote from the *Journal* with the customary acknowledgment of the source. To reprint a figure, table, or other excerpt requires the consent of one of the authors and notification to AIP.

Requests for Permission: Address requests to Penny Slattery, Journal Manager, Medical Physics Journal, AAPM, One Physics Ellipse, College Park, MD 20740-3846; Fax: 301-209-3399; Telephone: 301-209-3352; E-mail: penny@aapm.org.

Microform: *Medical Physics* is available on microfiche issued at the same frequency as the printed journal, and annually on microfilm. Direct requests to AIP: Circulation & Fulfillment/Single Copy Sales, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502; Fax 516-349-9704; Telephone: 800-344-6902 (U.S. and Canada) or 516-576-2270.

Online Availability: *Medical Physics* is available online at <http://www.medphys.org>. Abstracts of journal articles published by the AIP and Member Societies (and several other physics publishers) are available from AIP's SPIN Web Service (<http://ojps.aip.org/spinweb/>).

Medical Physics, Vol. 29, No. 7, July 2002

Dosimetric characterization of a bi-directional micromultileaf collimator for stereotactic applications M. Bucciolini, S. Russo, F. Banci Buonamici, S. Pini, and P. Silli	1456
Calculated absorbed-dose ratios, TG51/TG21, for most widely used cylindrical and parallel-plate ion chambers over a range of photon and electron energies R. C. Tailor and W. F. Hanson	1464
On the role of intensity-modulated radiation therapy in radiation oncology R. J. Schulz and A. Robert Kagan	1473
Calibration of new high dose rate ¹⁹²Ir sources K. E. Stump, L. A. DeWerd, J. A. Micka, and D. R. Anderson	1483
Multiple local minima in IMRT optimization based on dose-volume criteria Qiuwen Wu and Radhe Mohan	1514
Underdosage of the upper-airway mucosa for small fields as used in intensity-modulated radiation therapy: A comparison between radiochromic film measurements, Monte Carlo simulations, and collapsed cone convolution calculations C. Martens, N. Reynaert, C. De Wagter, P. Nilsson, M. Coghe, H. Palmans, H. Thierens, and W. De Neve	1528
Experimental investigation of dose calibrator response for ¹²⁵I brachytherapy solutions contained in 5 mL plastic syringes and 2 mL conical glass v-vials as a function of filling mass B. E. Zimmerman, J. T. Cessna, and J. A. Dorton	1547
Dose distributions for ⁹⁰Y intravascular brachytherapy sources used with balloon catheters Marleen Piessens, Nick Reynaert, Jaroslaw Potempa, Hubert Thierens, William Wijns, and Luc Verbeke	1562
Fast cross-projection algorithm for reconstruction of seeds in prostate brachytherapy Sreeram Narayanan, Paul S. Cho, and Robert J. Marks II	1572
Application of imaging-derived parameters to dosimetry of intravascular brachytherapy sources: Perturbation effects of residual plaque burden Varun Sehgal, Zuofeng Li, Jatinder R. Palta, Karen M. Smith, and W. E. Bolch	1580
On cold spots in tumor subvolumes Wolfgang A. Tomé and Jack F. Fowler	1590
Vessel size measurements in angiograms: A comparison of techniques Kenneth R. Hoffmann, Daryl P. Nazareth, László Miskolczi, Anant Gopal, Zhou Wang, Stephen Rudin, and Daniel R. Bednarek	1622

RADIATION IMAGING PHYSICS

Femoral neck trabecular patterns predict osteoporotic fractures Richard L. Lee, Jane E. Dacre, Deborah J. Hart, and Tim D. Spector	1391
Technical note: Creating a four-dimensional model of the liver using finite element analysis K. K. Brock, S. J. Hollister, L. A. Dawson, and J. M. Balter	1403
CdZnTe detector in diagnostic x-ray spectroscopy Satoshi Miyajima, Kotaro Imagawa, and Masao Matsumoto	1421
Kymogram detection and kymogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart Marc Kachelrieß, Dirk-Alexander Sennst, Wolfgang Maxlmoser, and Willi A. Kalender	1489
Development of a computerized method for identifying the posteroanterior and lateral views of chest radiographs by use of a template matching technique Hidetaka Arimura, Shigehiko Katsuragawa, Qiang Li, Takayuki Ishida, and Kunio Doi	1556
Image quality evaluation of flat panel and image intensifier digital magnification in x-ray fluoroscopy Yogesh Srinivas and David L. Wilson	1611
X-ray micro-CT with a displaced detector array Ge Wang	1634

(Continued)

ULTRASOUND PHYSICS

Computerized lesion detection on breast ultrasound

Karen Drukker, Maryellen L. Giger, Karla Horsch, Matthew A. Kupinski, Carl J. Vyborny,
and Ellen B. Mendelson 1438

MAGNETIC RESONANCE PHYSICS

Automatic delineation of Gd enhancements on magnetic resonance images in multiple sclerosis

Renjie He and Ponnada A. Narayana 1536

NUCLEAR MEDICINE PHYSICS

Image reconstruction algorithm for a rotating slit collimator

Gengsheng L. Zeng, Daniel Gagnon, Christopher G. Matthews, Jeffery A. Kolthammer, Jason D. Radachy,
and William G. Hawkins 1406

Precise real-time correction of Anger camera deadtime losses

Tilahun Woldeselassie 1599

LETTERS TO THE EDITOR

Monte Carlo determination of dose rate constant

Geoffrey S. Ibbott, Ali S. Meigooni, and Darren M. Gearheart 1637

Ph.D. THESES ABSTRACTS

Determination and use of radiobiological response parameters in radiation therapy optimization (in English)

Panayiotis Mavroidis 1639

ANNOUNCEMENTS

1640

AAPM COPYRIGHT

1642

Only when space allows will the list of Currently Available AAPM Publications and the Instructions to Authors appear in the printed version of *Medical Physics*. These are available anytime from the Medical Physics website at

<http://www.medphys.org>

Kymogram detection and kymogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart

Marc Kachelrieß,^{a)} Dirk-Alexander Sennst, Wolfgang Maxlmoser, and Willi A. Kalender
Institute of Medical Physics, University of Erlangen-Nürnberg, Germany

(Received 11 October 2001; accepted for publication 18 April 2002; published 20 June 2002)

Subsecond single-slice, multi-slice or cone-beam spiral computed tomography (SSCT, MSCT, CBCT) offer great potential for improving heart imaging. Together with the newly developed phase-correlated cardiac reconstruction algorithms 180°MCD and 180°MCI [Med. Phys. **27**, 1881–1902 (2000)] or related algorithms provided by the CT manufacturers, high image quality can be achieved. These algorithms require information about the cardiac motion, i.e., typically the simultaneously recorded electrocardiogram (ECG), to synchronize the reconstruction with the cardiac motion. Neither data acquired without ECG information (standard patients) nor acquisitions with corrupted ECG information can be handled adequately. We developed a method to extract the appropriate information about cardiac motion directly from the measured raw data (projection data). The so-called kymogram function is a measure of the cardiac motion as a function of time t or as a function of the projection angle α . In contrast to the ECG which is a global measure of the heart's electric excitation, the kymogram is a local measure of the heart motion at the z -position $z(\alpha)$ at projection angle α . The patient's local heart rate as well as the necessary synchronization information to be used with phase-correlated algorithms can be extracted from the kymogram by using a series of signal processing steps. The kymogram information is shown to be adequate to substitute the ECG information. Computer simulations with simulated ECG and patient measurements with simultaneously acquired ECG were carried out for a multislice scanner providing $M=4$ slices to evaluate these new approaches. Both the ECG function and the kymogram function were used for reconstruction. Both were highly correlated regarding the periodicity information used for reconstruction. In 21 out of 25 consecutive cases the kymogram approach was equivalent to the ECG-correlated reconstruction; only minor differences in image quality between both methods were observed. For one patient the synchronization information detected by the ECG monitor turned out to be wrong; here, the kymogram constituted the only approach that provided useful reconstructions. Patient studies with 12 and 16 slices indicate the usefulness of our approach for cone-beam CT scans. Kymogram-correlated reconstructions also appear to have the potential to improve imaging of pericardial lung areas in general. © 2002 American Association of Physicists in Medicine. [DOI: 10.1118/1.1487861]

Key words: Computed tomography (CT), multi-slice spiral CT (MSCT), cone-beam spiral CT (CBCT), heart, ECG, kymogram

I. INTRODUCTION

Noninvasive imaging of the heart is an important issue because coronary artery disease is one of the leading causes of death in western civilizations. Since most of the cardiac imaging techniques available today [cardiac ultrasound, fluoroscopy, conventional computed tomography (CT), spiral CT, electron-beam CT and magnetic resonance tomography] provide insufficient information or are not readily available¹ dedicated reconstruction algorithms using the simultaneously acquired patient electrocardiogram (ECG) as additional information for reconstruction have been developed in recent years.^{2–5} These algorithmic developments together with vast improvements in CT technology, namely the reduced rotation time down to 0.42 s per revolution and the introduction of multi-slice and cone-beam spiral CT (MSCT and CBCT) systems, allowed for the recent breakthrough of cardiac CT imaging.

For phase-correlated image reconstruction the user typically specifies a reconstruction phase c_R relative to the R

peaks of the ECG. For example, 70% of $R-R$ is a typical selection of the reconstruction phase. Alternatively, absolute timing specifications may be used. Due to the synchronous recording of the ECG signal, the cardiac ECG phase $c_E(\alpha)$ is known for each view angle α . This information allows to use only those raw data for reconstruction that are as close as possible to c_R . In other words, the phase-correlated reconstruction algorithms use data windows that satisfy $c_E(\alpha) \approx c_R$ for reconstruction.

Two classes of phase-correlated algorithms are in use today: Partial scan approaches that use 180° data intervals and cardio interpolation approaches that combine data of adjacent heart cycles and rotations to improve temporal resolution. Advantages of the interpolation algorithms over the partial scan algorithms have been demonstrated clearly.^{2–4,6} These findings are also reflected by current investigations of other groups and by the manufacturers who recently started to switch from half scan or partial scan to “multisector” or “pulse-rate adaptive” reconstruction algorithms.^{7,8}

In this paper, we propose an alternative measure of cardiac motion that may serve as a fall-back solution to substitute the use of the cardiac ECG phase $c_E(\alpha)$ or that may be applied in situations where no ECG is available or where using ECG acquisition is inconvenient.

The motion detection shall be computationally efficient in order not to increase the total reconstruction time. A raw data-based approach appears to be most promising. The function to be extracted from the raw data is called the kymogram; the synchronization information derived therefrom is the cardiac kymogram phase and is denoted by $c_K(\alpha)$. (We have chosen the term kymogram to give credit to conventional kymogram methods that are available since the mid-19th century and that use an instrument to graphically record variations or undulations, as of the heart and blood vessels but also of the vocal chord. The name kymogram is derived from kymo, the water nymph of greek mythology. Further information can be found at www.kymogram.com)

We derive the kymogram function using a raw data-based COM (center of mass) tracking, followed by a few signal processing steps.⁹ This paper specifies the algorithms and demonstrates the performance of the kymogram detection in a simulation study, in one cadaver and in a patient study including 25 individuals consecutively scheduled for coronary CT angiography. Comparisons to ECG-correlated cardiac imaging and to standard (not phase-correlated) reconstructions are given.

II. MATERIALS AND METHODS

Throughout this paper we use the notations and definitions stated in the list below. The variables α (fan-beam projection angle), ϑ (parallel beam projection angle), t (time of a projection), and z (z position of a projection) are related as

$$\frac{\alpha}{2\pi} = \frac{\vartheta}{2\pi} = \frac{t}{t_{\text{rot}}} = \frac{z}{d}.$$

We will make use of this one-to-one correspondence to switch between these variables, if convenient.

*	convolution symbol
$\delta(\cdot)$	Dirac's delta function
$\Pi(\cdot)$	rectangle function with support $[-\frac{1}{2}, \frac{1}{2}]$ and area 1
$\Pi_a^*(\cdot)$	$(1/ a)\Pi(\cdot/a)$
$\text{sinc}(\cdot)$	sinc-function, $\text{sinc}(x) = \sin(\pi x)/\pi x$
α	projection angle, $\alpha \in [0, 2\pi)$ for a sequence (360°) scan or z-interpolated data, $\alpha \in \mathbb{R}$ for a spiral scan
β	angle within fan, $\beta \in [-\frac{1}{2}\Phi, \frac{1}{2}\Phi]$
c_R	cardiac reconstruction phase (the center phase of the data used for reconstruction)
$c_\chi(t)$	cardiac phase as a function of time, $c_\chi(t) \in [0, 1)$. $\chi = E$ for ECG, $\chi = K$ for kymogram, and $\chi = S$ for simulated functions

$C_\chi(t)$	absolute cardiac phase given as $C_\chi(t) = n + c_\chi(t)$ where n denotes the number of heart beats that have already occurred
Δc_χ	constant phase offset to be added to the kymogram phase (modulo 1) to best agree with $c_\chi(t)$
d	table feed distance per 360° rotation
Φ	fan angle, in our case $\Phi = 52^\circ$
f_H	patient's heart rate, typically $40 \text{ min}^{-1} \leq f_H \leq 120 \text{ min}^{-1}$
$L_\chi(t)$	phase lag function, $L_\chi(t) = C_\chi(t) - C_K(t)$
M	number of simultaneously scanned slices
p	pitch, $p = d/MS$
$p(\alpha, \beta)$	fan-beam projection data (neglecting the z-component of the detector)
$p(\vartheta, \xi)$	parallel-beam projection data (neglecting the z-component of the detector)
S	nominal slice thickness
t_{rot}	time for a 360° rotation
$x_c(\cdot), y_c(\cdot)$	center-of-mass coordinates as a function of the view angle ϑ , of time t , or of z-position z (we have the equivalence $\vartheta/2\pi = t/t_{\text{rot}} = z/d$)
$x_{uc}(\cdot), y_{uc}(\cdot)$	coordinates of the unbiased center of mass
$x'_{uc}(\cdot), y'_{uc}(\cdot)$	coordinates of the unbiased center of mass given in the local inertia coordinate system
$x_{buc}(\cdot), y_{buc}(\cdot)$	coordinates of the bandpass filtered, unbiased center of mass
$x'_{buc}(\cdot), y'_{buc}(\cdot)$	coordinates of the bandpass filtered, unbiased center of mass given in the local inertia coordinate system
z axis	axis of rotation
z_R	arbitrary selectable reconstruction position
(C/W)	notation used for the window setting, C is the window's center in HU, W its width in HU

The freely selectable parameter c_R is used to select the desired cardiac phase; c_R determines the relative center of the time window with respect to each R - R interval of the ECG or relative to the kymogram period. Arithmetics using the cardiac phase c are meant to be modulo 1 to take into account its periodicity.

Patient and cadaver measurements were performed on a SOMATOM Volume Zoom MSCT scanner (Siemens Medical Solutions, Forchheim, Germany). The scan protocol used for 25 cardiac patients is the MSCT coronary angiography protocol $t_{\text{rot}} = 0.5 \text{ s}$, $M \times S = 4 \times 1 \text{ mm}$, $d = 1.5 \text{ mm}$ (i.e., $p = 0.375$) which is established today as a standard scan protocol for thin-section cardiac CTA (CT angiography) with 4-slice CT systems.^{5,6,10,11}

We also performed standard thorax scans with 16-slices and coronary angiography scans with 12-slices on a SOMATOM Sensation 16 CBCT scanner (Siemens Medical Solu-

tions, Forchheim, Germany). The standard thorax protocol was $t_{\text{rot}} = 0.5$ s, $M \times S = 16 \times 0.75$ mm, $d = 6.0$ mm (i.e., $p = 0.5$) and covers a range of 360 mm in 30 s. The cone-beam coronary angiography protocol we used was $t_{\text{rot}} = 0.42$ s, $M \times S = 12 \times 0.75$ mm, $d = 3.0$ mm (i.e., $p = 0.333$) and covers 160 mm in 22 s. Our Sensation 16 is a work-in-progress installation without ECG option and hence we cannot quantitatively assess the kymogram results for those patients scanned on the cone-beam CT.

Further, spiral cone-beam data for a 4-slice and a 12-slice scanner of the cardiac motion phantom (see Ref. 3 for a description thereof) were simulated using the dedicated simulation software ImpactSIM (VAMP GmbH, Möhrendorf, Germany).

The kymogram detection algorithm is implemented as the Kymo taskcard of the Syngo Explorer (VAMP GmbH, Möhrendorf, Germany). The algorithm generates an ECG compatible kymogram file from the raw data which is stored in the DICOM database of Syngo™ (Siemens Medical Solutions, Erlangen, Germany). The file is then used to synchronize the phase-correlated reconstruction algorithms.

Reconstructions are performed with the cardio interpolation approach 180°MCI (Multi-slice cardio interpolation) and ASSR CI (advanced single-slice rebinning cardio interpolation) for 4-slice and 16-slice data, respectively.^{3,12} The reconstruction algorithms are implemented on a standard PC using the dedicated image reconstruction and image evaluation software ImpactIR (VAMP GmbH, Möhrendorf, Germany).

III. KYMOGRAM DETECTION

A. Center of mass tracking

The first step in the kymogram detection approach which we present here is to compute an estimate of the center of mass of the slice currently scanned. Our method is stimulated by and is a generalization of the algorithm published in Ref. 13. We make use of the well-known fact that the COM of the object projects for each parallel view angle ϑ onto the COM of the parallel projection. To establish this fact, we denote the parallel projection through an object $\mu(x, y)$ in two dimensions as

$$p(\vartheta, \xi) = \int dx dy \mu(x, y) \delta(x \cos \vartheta + y \sin \vartheta - \xi).$$

Now, one can immediately validate the following properties which hold $\forall \vartheta$:

$$\int dx dy \mu(x, y) = \int d\xi p(\vartheta, \xi) \quad (\text{conservation of mass}), \quad (1a)$$

$$\begin{pmatrix} \cos \vartheta \\ \sin \vartheta \end{pmatrix} \cdot \int dx dy \begin{pmatrix} x \\ y \end{pmatrix} \mu(x, y) = \int d\xi \xi p(\vartheta, \xi) \quad (\text{conservation of first moment}). \quad (1b)$$

These relations state that the COM of the object function projects onto the COM of the corresponding parallel projection.

Therefore, it seems promising to use the measured projection data to compute the projection COM $\xi_c(\vartheta)$ for each parallel view angle ϑ and to estimate the object COM therefrom. For moving objects, the object COM will also vary in time—and thus as a function of ϑ —and hence the function $\xi_c(\vartheta)$ should allow us to draw conclusions on the object motion provided that a small range of ϑ , say an interval of length $2\pi f$ with f denoting the fraction of a full rotation contributing to the estimation procedure, suffices to perform the estimation.

The scan geometry is a fan-beam geometry with a single-slice, multi-slice or cone-beam spiral trajectory, but we are in need of 2D parallel data to use the relations derived above. Hence, we must convert the measured data accordingly. Fortunately, it suffices to regard the central slice only, and one may neglect the fact that the table translates by a distance of $d(f + \Phi/\pi)$ while acquiring the data needed for one COM estimation. Experiments showed that neither taking into account more slices nor compensating for the table movement by performing a z -interpolation between adjacent detector slices improve the outcome of our study. This can be explained by the signal processing steps that follow the COM detection. They remove all biased dependencies along the z direction (see below) and the algorithm becomes insensitive to axial variations. Due to these reasons, the following considerations neglect the table movement and all but the central detector slice.

To perform the conversion between fan-beam and parallel-beam geometry we denote the measured projection data as $p(\alpha, \beta)$ with $\alpha \in \mathbb{R}$ being the rotation angle of the gantry and $\beta \in \frac{1}{2}[-\Phi, \Phi]$ being the angle within the fan. We need the center of mass of each projection in parallel coordinates as a function of ϑ , i.e., $\xi_c(\vartheta)$. Due to the known relations $\xi = -R_F \sin \beta$, where R_F denotes the distance of the focal spot to the isocenter, and $\alpha = \vartheta - \beta$ we can change the integration variable ξ to β by using the Jacobian $d\xi = -R_F \cos \beta d\beta$ and get

$$\begin{aligned} \xi_c(\vartheta) &= \frac{\int d\xi \xi p(\vartheta, \xi)}{\int d\xi p(\vartheta, \xi)} \\ &= -\frac{\int d\beta R_F^2 \sin \beta \cos \beta p(\vartheta - \beta, \beta)}{\int d\beta R_F \cos \beta p(\vartheta - \beta, \beta)} \\ &= -\frac{1}{2} R_F \frac{\int d\beta \sin(2\beta) p(\vartheta - \beta, \beta)}{\int d\beta \cos \beta p(\vartheta - \beta, \beta)}. \end{aligned}$$

As mentioned, no correction for the shift in z direction is made. Further, one notes that the data contributing to $\xi_c(\vartheta)$ stems from a gantry angle range of size Φ and therefore contains temporal contributions of size $t_{\text{rot}} \Phi / 2\pi$ which is far

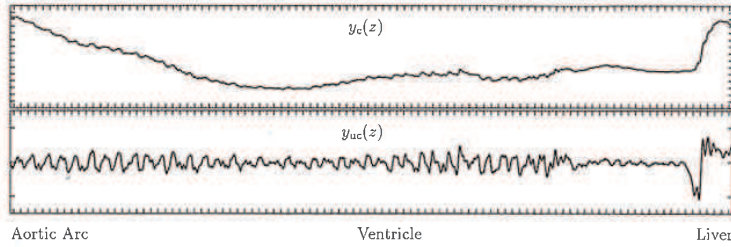


FIG. 1. Biased and unbiased y coordinate of the estimated COM as a function of the z position. The tick mark spacing is 1 mm in z and y direction.

below the time of one cardiac cycle. Since the heart, as the moving part of the object, occupies only a small fraction of the complete field of measurement (which corresponds to the fan angle Φ) the temporal contributions of the heart to the computation of ξ_c are even less and can be neglected.

Denoting the image center of mass as x_c and y_c we have shown that

$$x_c \cos \vartheta + y_c \sin \vartheta - \xi_c(\vartheta) = 0$$

should hold $\forall \vartheta$. This can be solved in a least square manner by minimizing

$$\frac{1}{2\pi f} \int_{\vartheta-f\pi}^{\vartheta+f\pi} d\vartheta (x_c \cos \vartheta + y_c \sin \vartheta - \xi_c(\vartheta, m))^2$$

in the range $[\vartheta-f\pi, \vartheta+f\pi]$ with $f > 0$. In the following we will formulate the integral as a convolution with $\Pi_{2\pi f}^*(\vartheta)$, for convenience. The minimization (derivative with respect to x_c and y_c) yields the system of equations

$$\begin{pmatrix} 1+C & S \\ S & 1-C \end{pmatrix} \begin{pmatrix} x_c \\ y_c \end{pmatrix} = \begin{pmatrix} X_C \\ X_S \end{pmatrix}$$

with the solution

$$\begin{pmatrix} x_c \\ y_c \end{pmatrix} = \frac{1}{1-C^2-S^2} \begin{pmatrix} 1-C & -S \\ -S & 1+C \end{pmatrix} \begin{pmatrix} X_C \\ X_S \end{pmatrix},$$

where we use the abbreviations

$$C = \cos(2\vartheta) * \Pi_{2\pi f}^*(\vartheta) = \text{sinc } 2f \cos 2\vartheta,$$

$$S = \sin(2\vartheta) * \Pi_{2\pi f}^*(\vartheta) = \text{sinc } 2f \sin 2\vartheta,$$

$$X_C = 2\xi_c(\vartheta) \cos(\vartheta) * \Pi_{2\pi f}^*(\vartheta),$$

$$X_S = 2\xi_c(\vartheta) \sin(\vartheta) * \Pi_{2\pi f}^*(\vartheta).$$

It should be noted that the denominator, which is the determinant of the coefficient matrix, yields $1-C^2-S^2=1-\text{sinc}^2 2f$ which is always positive and thus indicates the regularity of the coefficient matrix. The fraction f should not be chosen too small to avoid numerical instabilities. Values f between 10% and 50% turn out to be sufficient to yield accurate results. The overall results do not depend on the exact choice of f ; we use $f=10\%$ in the following.

B. Further signal processing

The COM signal we have computed in the preceding section needs to undergo a few signal processing steps until the synchronization peaks of the cardiac motion can be detected.

For convenience, we will now switch from the independent variable ϑ to the variable $t = t_{\text{rot}} \vartheta / 2\pi$ which denotes the time or to the variable $z = d \vartheta / 2\pi$ which denotes the z position. Functions of ϑ are now overloaded and we also note t or z as the function's argument. Thereby, we emphasize which parameter is of relevance. For example, when smoothing the function in the z direction we use z and when performing a temporal filtering we use t while being aware that there is a one-to-one correspondence between ϑ , t , and z .

Further, if the x component is the only component noted it is implicitly assumed that the y component and other motion components are treated equivalently.

1. Bias correction

The COM functions $x_c(t)$ and $y_c(t)$ are biased due to (slow) variations in the patient cross section introduced by the continuous translation of the patient table during the spi-



FIG. 2. Parametric plot (x_{uc} vs y_{uc} as a function of t) of the unbiased COM for a complete scan (many heart cycles). The grid spacing is 0.1 mm. The corresponding cardiac ECG phase $c_E(t)$ has been used to set the hue of the plot. The legend shows the hue to phase mapping. Regions of similar hue are spatially relatively close. The two global principal axes are shown as well. Their length was chosen proportional to Θ'_{xx} and Θ'_{yy} , respectively. For this patient we have $\Theta'_{xx}=6.8\Theta'_{yy}$ and $\phi=29.5^\circ$.

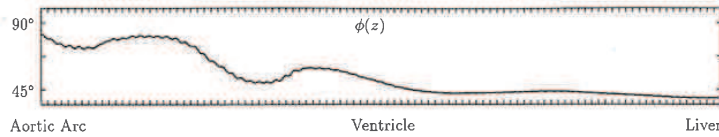


FIG. 3. The function $\phi(z)$ for the complete scan. Ticks are spaced at 1 mm in the z direction and 22.5° in the ϕ direction, respectively.

ral scan. To remove the bias we subtract the running mean of the COM using a rectangular filter of width Δt . Thus, the unbiased version of the signal is given as

$$x_{uc}(t) = x_c(t) - x_c(t) * \Pi_{\Delta t}^*(t).$$

A value of $\Delta t = 1$ s is large enough to avoid averaging out components of the cardiac motion. The value is motivated by the fact that cardiac motion usually is of the order $f_H \geq 60 \text{ min}^{-1}$. Anyhow, frequencies below this are suppressed smoothly by the bias procedure and heart rates down to about 30 bpm can be detected as well.

To illustrate the necessity of bias correction Fig. 1 shows the functions $y_c(z)$ and $y_{uc}(z)$ for a typical patient. The unbiased signal is of low amplitude (submillimeter); its variations are mainly due to cardiac motion.

2. Principal heart axes

The two available signals $x_{uc}(z)$ and $y_{uc}(z)$ represent an estimate of the in-plane cardiac motion as a function of time or of z position. We now seek to reduce the information to a one-dimensional signal from which we can easily detect synchronization peaks.

Assume that cardiac motion takes place in the y direction only. Then, the signal in x direction would be low and probably worthless. A parametric plot of $(x_{uc}(z), y_{uc}(z))$ as a function of z for a typical patient indicates that there is a preferred axis of in-plane motion (Fig. 2). Projecting the COM functions onto this principle axis of motion should consequently yield a useful COM function even if the motion takes place along one axis only.

We determine the principal axis of motion (and its orthogonal counterpart) by taking the inertia tensor

$$\Theta(t) = \begin{pmatrix} \Theta_{xx} & \Theta_{xy} \\ \Theta_{xy} & \Theta_{yy} \end{pmatrix}(t)$$

$$\Theta_{xx}(t) = \Pi_{\Delta t}^*(t) * x_{uc}^2(t),$$

with the moments of inertia defined as

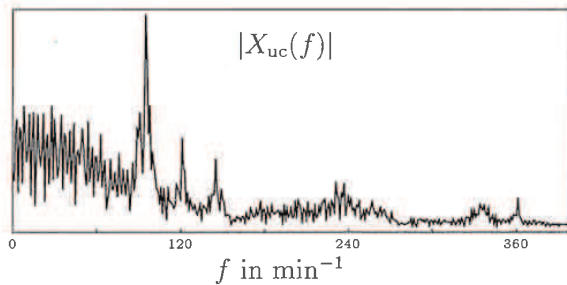


FIG. 4. Spectrum of $x'_{uc}(t)$ scaled to arbitrary units for frequencies up to 400 min^{-1} . Patient heart rate is 97 min^{-1} which obviously coincides with the dominating peak.

$$\Theta_{xy}(t) = \Pi_{\Delta t}^*(t) * x_{uc}(t) y_{uc}(t),$$

$$\Theta_{yy}(t) = \Pi_{\Delta t}^*(t) * y_{uc}^2(t).$$

Then, we perform a principal axes transformation such that the transformed moment of inertia is diagonal,

$$\Theta'(t) = \begin{pmatrix} \Theta'_{xx} & 0 \\ 0 & \Theta'_{yy} \end{pmatrix}(t).$$

The width Δt of the contributing running interval is chosen as $\Delta t = 10$ s to cover at least about 10 heart beats (assuming a heart rate of at least 60 beats per minute).

The diagonal values of Θ' are the eigenvalues of Θ . Without loss of generality we demand $\Theta'_{xx} \geq \Theta'_{yy}$. We denote the corresponding rotation angle of the underlying orthogonal transformation as $\phi(t)$ and we use the transformation matrix to express the COM coordinates in the new eigensystem

$$\begin{pmatrix} x'_{uc}(t) \\ y'_{uc}(t) \end{pmatrix} = \begin{pmatrix} \cos \phi(t) & \sin \phi(t) \\ -\sin \phi(t) & \cos \phi(t) \end{pmatrix} \begin{pmatrix} x_{uc}(t) \\ y_{uc}(t) \end{pmatrix}.$$

Here, $x'_{uc}(t)$ is expected to be the most pronounced signal since it corresponds to the main inertia axis (largest eigenvalue).

The advantage of computing the new coordinate system adaptively, i.e., over a range Δt , is that the algorithm can adopt to changing (e.g., slowly rotating) principal axes.

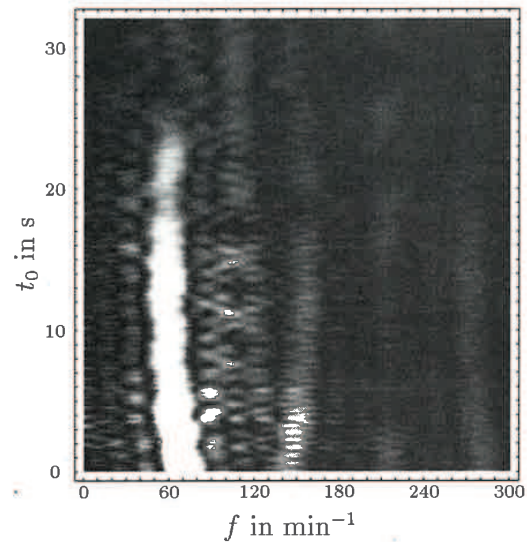


FIG. 5. The windowed Fourier transform $X_{uc}(f, t_0)$ for frequencies up to 300 min^{-1} . The patient's heart rate lies between 60 min^{-1} and 70 min^{-1} . For further discussion of this specific patient see Sec. V C.

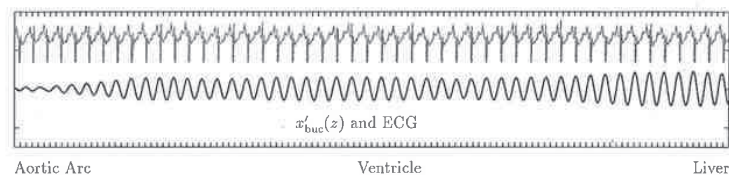


FIG. 6. Kymogram $x'_{buc}(t)$ and the ECG signal as a function of z position/time. Tick spacing is 1 mm in the z direction and in the x' direction; the ECG signal is scaled to arbitrary units.

Since this range constitutes the average of at least 10 cardiac cycles, the determination of the heart axis is insensitive to extra systoles or arrhythmic behavior.

For illustration purposes the principal axes shown in Fig. 2 are the global ($\Delta t = \infty$) axes and do not reflect the adaptive behavior of the algorithm. The function $\phi(t)$ is shown in Fig. 3 for another patient.

3. Bandpass filtering

The quality of the unbiased COM signal proved to be insufficient to directly detect periodicity information. The spectrum of $x_{uc}(t)$ and $y_{uc}(t)$ —a patient example is given in Fig. 4—shows dominating peaks at the heart frequency f_H and at the scanner's rotation frequency $1/t_{rot}$.

Therefore, a bandpass filter must be centered about f_H to remove the undesired parts of the spectrum. Since the heart frequency may change as a function of time, e.g., from 60 min^{-1} at scan start to 100 min^{-1} at scan end, a simple bandpass filter will not suffice. We rather perform a windowed Fourier transform assuming a time window $w(t)$ with $\int dt w^2(t) = 1$:

$$X_{uc}(f, t_0) = \int dt x_{uc}(t) w(t - t_0) e^{-2\pi i f t}.$$

The window function used is

$$w(t) = \frac{2}{\sqrt{3\Delta t}} \cos^2\left(\frac{\pi}{2} \frac{t}{\Delta t}\right) \Pi\left(\frac{1}{2} \frac{t}{\Delta t}\right).$$

An appropriate width, that allows to detect frequencies down to 20 min^{-1} is $\Delta t = 3$ s. Hence, all clinically relevant cases ($f_H > 40 \text{ min}^{-1}$) can be handled.

From the modulus of these functions we detect the maximum. The frequencies taken into account lie between 40 min^{-1} and $1/t_{rot}$. The frequency where this maximum occurs is denoted as $f_H(t_0)$ and bandpass filtering is performed by multiplying the windowed Fourier transform with a smooth function H that is centered about $f_H(t_0)$.

$$X_{buc}(f, t_0) = X_{uc}(f, t_0) H(f - f_H(t_0)).$$

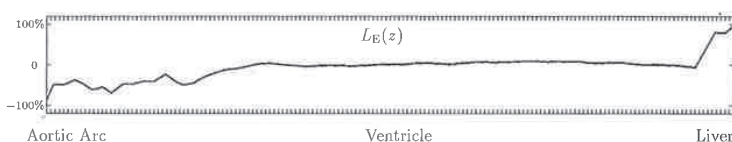


FIG. 7. An example ECG lag function $L_E(z)$ corresponding to the ECG and kymogram shown in Fig. 6.

Currently, we use

$$H(f) = \cos^2\left(\frac{\pi}{2} \frac{f}{\Delta f_H}\right) \Pi\left(\frac{1}{2} \frac{f}{\Delta f_H}\right),$$

where Δf_H denotes the full width at half maximum of the bandpass filter function. A value of $\Delta f_H = 20 \text{ min}^{-1}$ turned out to be sufficient. We have tested the method with varying values of Δf_H and found the method to be stable for values between 10 and 30 min^{-1} (which is also indicated by the width of the peak in Fig. 4). An example of a windowed Fourier transform for a typical patient is given in Fig. 5.

The temporal domain signal is then reconstructed by simple inversion:

$$x_{buc}(t) = \int \int dt_0 df X_{buc}(f, t_0) w(t - t_0) e^{2\pi i f t}.$$

The kymogram function $x'_{buc}(t)$ and the patient's ECG signal are shown in Fig. 6; the close correlation of the periodicity information of these two signals is apparent.

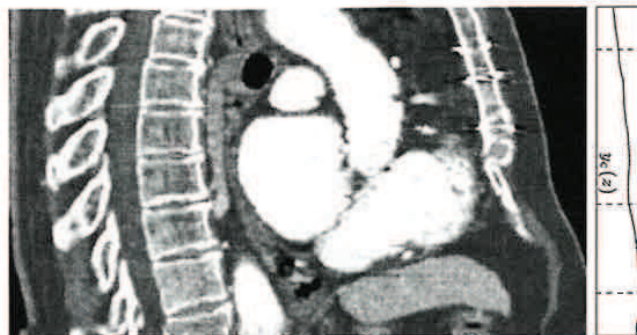
4. Peak detection

Finally, the synchronization peaks are detected from $x'_{buc}(t)$ by simply detecting the ascending zero crossings of the first derivative. If we denote the location of the peaks as t_n we construct the cardiac kymogram phase as

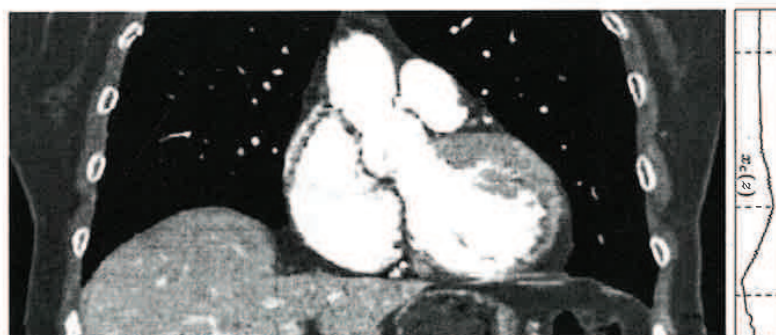
$$c_K(t) = \frac{t - t_n}{t_{n+1} - t_n} + \Delta c_K \bmod 1$$

with n such that $t_n \leq t < t_{n+1}$.

This definition is equivalent to the definition of the cardiac ECG phase $c_E(t)$ which quantifies the location of t relative to the previous and next R peak. The constant offset Δc_K reflects the remaining degree of freedom in choosing the kymogram phase. If we do not intend to compare our results to an ECG function, we set this offset to zero. For ECG comparisons, however, we choose its value to minimize the phase-lag between ECG and kymogram (see below). Doing so, we can, for example, reconstruct ECG and kymogram correlated at a reconstruction phase of $c_R = 70\%$ while ensuring maximum consistency between the two reconstructed



a) Sagittal MPR



b) Coronal MPR



c) Transaxial slices (in cranio-caudal order)

FIG. 8. MPRs and transaxial slices of the complete patient thorax exemplify the behavior of the COM curves. (a) Sagittal section and $y_c(z)$. (b) Coronal section and $x_c(z)$. The global behavior of the COM coordinates correlates well with the anatomy shown. (c) Transaxial slices for illustration purposes. Their z positions correspond to the dashed lines of the x_c and y_c plots. The images are reconstructed kymogram-correlated.

volumes. Without the offset correction it could happen that kymogram images at, say, 70% are best comparable to ECG images at 43%.

IV. TEST METHODS

A. Comparing $c_K(t)$ and $c_X(t)$

We define the monotonically increasing (absolute) phase function

$$C_X(t) = n + c_X(t) \quad \text{with } n \text{ such that } t_n \leq t < t_{n+1}.$$

The integer part of C_X counts the number of heart beats that have occurred and the fractional part gives the relative position between two synchronization points. Obviously, C_X is strictly monotonically increasing in t and has an inverse which we denote as C_X^{-1} . Now, we can regard the phase lag function

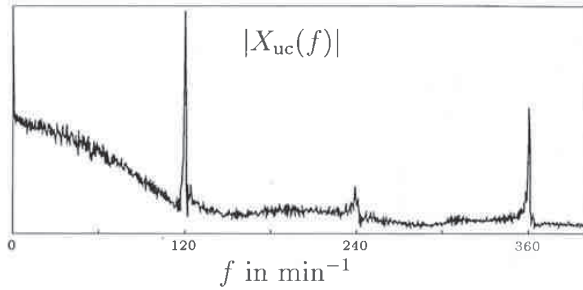


FIG. 9. Spectrum of $x'_{uc}(t)$ as a function of frequency f for the cadaver scan. The peaks at $1/t_{rot}$ and multiples thereof are clearly visible. The ordinate is scaled to arbitrary units.

$$L_{\chi}(t) = C_{\chi}(t) - C_K(t)$$

which should be constant for an ideal correlation between the ECG and the kymogram approach. The ECG lag for a typical patient is given in Fig. 7. Please note the plateau in the scan center which indicates a good correlation between ECG and kymogram for the plateau region. The plateau's height is within 5% distance to 0% due to the offset correction Δc_{χ} . Since the heart is not reached fully at scan start and since the scan has left the heart at scan end there are deviations from the 0% optimum at the left and right side of the plot.

B. Simulated motion functions

For test purposes, we simulated phantom data of our cardiac motion phantom using various motion functions. It turned out that the computation of $\xi_c(\vartheta)$ based on these simulated raw data yields exactly the same result as when directly prescribing

$$\xi_c(\vartheta) = x_{sim}(\vartheta) \cos \vartheta + y_{sim}(\vartheta) \sin \vartheta \quad (2)$$

with $\vartheta = 2\pi t/t_{rot}$ and the COM coordinates $x_{sim}(\vartheta)$ and $y_{sim}(\vartheta)$. Since our intent is to evaluate the kymogram detection algorithm we will therefore not concentrate on the simulated raw data but on the directly generated function ξ_c and its evaluation.

Thus, we simulated a number of COM-functions $x_{sim}(t)$ and $y_{sim}(t)$ and used (2) to compute the projected COM. To complete our simulation, we had to additionally define the sync peaks t_n of the simulated motion. This defines the simulated phase $c_S(t)$ and the absolute phase $C_S(t)$.

The simulated input signal $\xi_c(\vartheta)$ was then used for the described signal processing steps that detect the kymogram peaks. The detected peaks are compared to the simulated sync peaks by computing the phase lag function $L_S(t)$ for simulated motion.

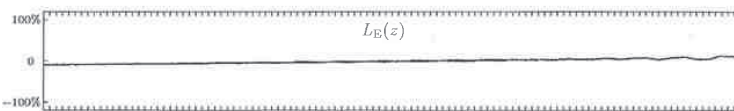


FIG. 10. The chirp's lag function $L_S(z)$. The frequency of motion increases linearly with the z position from 40 min^{-1} to 110 min^{-1} . The tick spacing in z direction is 1 mm.

1. Sine

As a simple test function we used a sine function in x direction defined in $0 \leq t \leq 40$ s:

$$x_{sim}(t) = 1.0 \text{ mm} \times \sin(2\pi t \times f_H),$$

$$y_{sim}(t) = 0,$$

the heart rates were chosen as $f_H = 60 \text{ min}^{-1}$, 70 min^{-1} , 80 min^{-1} , and 100 min^{-1} . We define the sine's sync peaks as the ascending zeroes of the motion's x component:

$$t_n = n/f_H \quad \text{with } 0 \leq n \leq f_H \times 40 \text{ s}.$$

2. Chirp

As a more complicated test function we define a chirp signal in the x direction. The increasing heart rate helps to evaluate the performance of our kymogram algorithms with patients of slowly varying heart rate.

For $0 \leq t \leq T = 40$ s we define

$$\begin{aligned} x_{sim}(t) = & 5.0 \text{ mm} \quad \text{constant offset} \\ & + 0.1 \text{ mm} \times \sin(2\pi t/(20t_{rot})) \quad \text{low frequency bias} \\ & + 1.0 \text{ mm} \times \sin(2\pi t(at+b)) \quad \text{actual signal} \\ & + 1.0 \text{ mm} \times \sin(2\pi t/t_{rot}) \quad \text{high frequency drop in} \\ & + 1.0 \text{ mm} \times \sin(4\pi t/t_{rot}) \quad \text{first harmonic of drop in} \\ y_{sim}(t) = & 0 \end{aligned}$$

to compute $\xi_c(\vartheta) = x_{sim}(\vartheta) \cos \vartheta + y_{sim}(\vartheta) \sin \vartheta$. The actual signal is a chirp starting with $f_H(0) = b = 40 \text{ min}^{-1}$ and ending with $f_H(T) = 2aT + b = 110 \text{ min}^{-1}$ (a and b have been chosen accordingly). Our aim is to observe the behavior of the kymogram detection during the frequency sweep from 40 min^{-1} to 110 min^{-1} . The drop in at $1/t_{rot} = 120 \text{ min}^{-1}$ and its harmonic mimic the resonance behavior of the scanner.

The function's sync peaks t_n are defined as the ascending zeroes of the actual signal

$$t_n(at_n + b) = n.$$

V. RESULTS

The following results are based on detecting synchronization information from x'_{buc} which has turned out, as expected, to be the most pronounced signal.

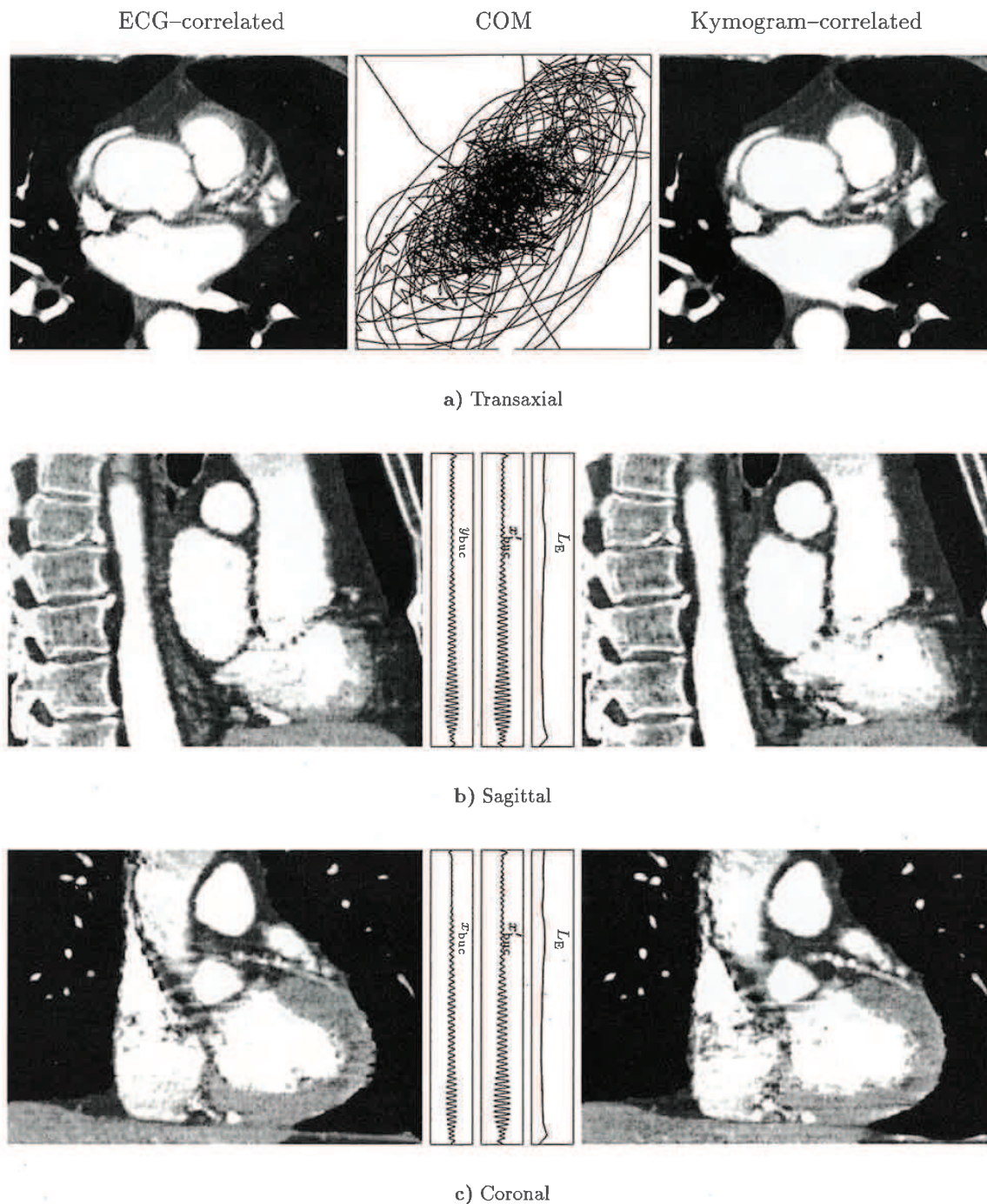


FIG. 11. Transaxial and MPR images of a cardiac patient reconstructed with 180° MCI. The parametric COM plot ranges from -0.75 mm to 0.75 mm for the unbiased x and y direction. The functions shown with the MPRs are aligned to the MPRs in z direction. The x and y dimensions are scaled to fit the available space. The lag function $L_E(z)$ and the primed x coordinate $x'_{buc}(z)$ are identical for both MPR sections; they are repeated to show the correlation to the anatomy. The patient's mean heart rate is $f_H = 65 \text{ min}^{-1}$ and the reconstruction phase was chosen as $c_R = 50\%$.

A. General results

To demonstrate the good correlation between the detected COM functions x_c and y_c as a function of the z position we

have prepared Fig. 8. It shows a sagittal and a coronal multiplanar reformation (MPR) of the complete thorax cross section (and not only of the heart) together with the corresponding COM estimation. In addition, three transaxial slices are



a) Standard reconstruction



b) ECG-based reconstruction



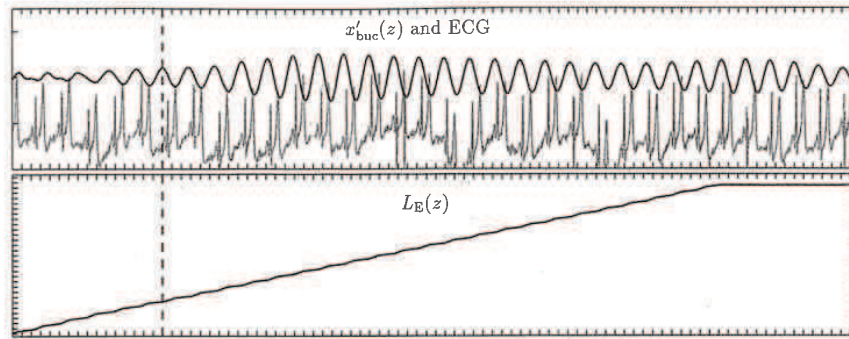
c) Kymogram-based reconstruction

FIG. 12. Comparison of a standard reconstruction with the phase-correlated ECG based and kymogram based reconstructions. Transaxial, sagittal, and coronal slices are shown. The patient's mean heart rate is $f_H = 52 \text{ min}^{-1}$ and the reconstruction phase was chosen as $c_R = 50\%$.

shown. The COM's slow variations, i.e., the bias that is to be removed, corresponds to the patient's anatomy. The shift at the lower end of the coronal plot, for example, is induced by the transition from the heart to the liver which introduces a shift of x_c towards the patient's right side (appearing left in the image).

To determine the source of the 120 min^{-1} resonance frequency that was visible in the spectral plots of Sec. III B 3 and that appears for all patient data, we have scanned a

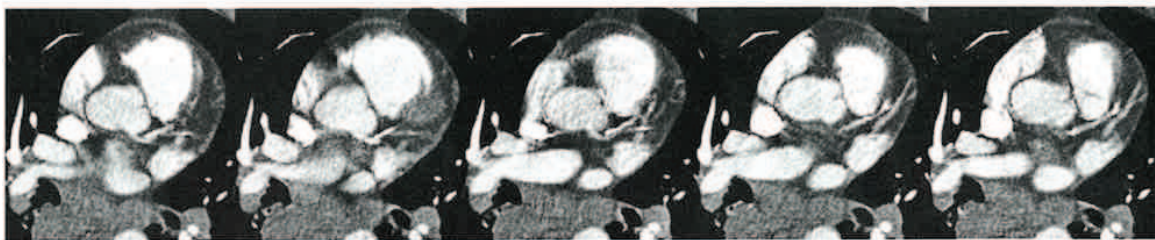
cadaver. As can be seen from Fig. 9 the resonance frequency appears even for motionless objects. Tests with simulated monochromatic raw data (pure line integrals) using the same scanner geometry showed no such resonance behavior. Consequently, nonlinear effects such as scattering and beam hardening have to be considered as the cause of this artifact. These nonlinearities violate the assumptions of (1) and therefore introduce an artificial modulation into the COM curve. Due to this intrinsic resonance, we cannot detect cardiac mo-



a) Kymogram, ECG and lag function



b) ECG-based reconstruction



c) Kymogram-based reconstruction

FIG. 13. For this patient, the *T* wave was misinterpreted as an *R* peak by the ECG monitor. The lag function therefore shows a strong increase, except for the last fifth of the scan where the ECG monitor started to correctly interpret the ECG signal. Tick spacing is 1 mm in the *z* direction, 1 mm for x'_{buc} and 100% for the lag function, respectively. The ECG is scaled to arbitrary units. The vertical dashed line indicates the slice position of the transaxial images. The reconstructions are performed in cardiac ECG- and kymogram-phase steps of 20%. The ECG-correlated images are blurred and show overlaid structures since different cardiac phases are mixed into each image. The patient's mean heart rate, as detected by the kymogram algorithm, is $f_H = 68 \text{ min}^{-1}$ and the reconstruction phases were chosen in steps of 20%.

tion at $f_H = 1/t_{\text{rot}}$ and within a 10% window around this frequency. This disadvantage will become irrelevant with future scanners that rotate faster.

B. Simulation study

The resulting lag functions for the simulated sine motions show no lag between the detected and the simulated peaks, i.e., $L_S(z) \equiv 0$. This is a first indication that the new method is free of systematic errors.

The chirp function, which is much more demanding, yields almost optimal results for the complete frequency range. This is indicated by the chirp's lag function in Fig. 10. The lag values are not perfectly zero. They rather increase

almost linearly from -5% to $+5\%$. This can be well accepted regarding the facts that (a) these small deviations are not oscillating but change slowly over the scan and (b) the range of heart rates covered with this experiment within a single scan is far from clinical reality.

C. Patient results

To evaluate our approach we have studied data of 25 routine patients scheduled for coronary CT angiography. Phase-correlated reconstructions were performed using the ECG-based and the kymogram-based approach for comparison. In addition, standard reconstructions which are not phase-correlated have been carried out.

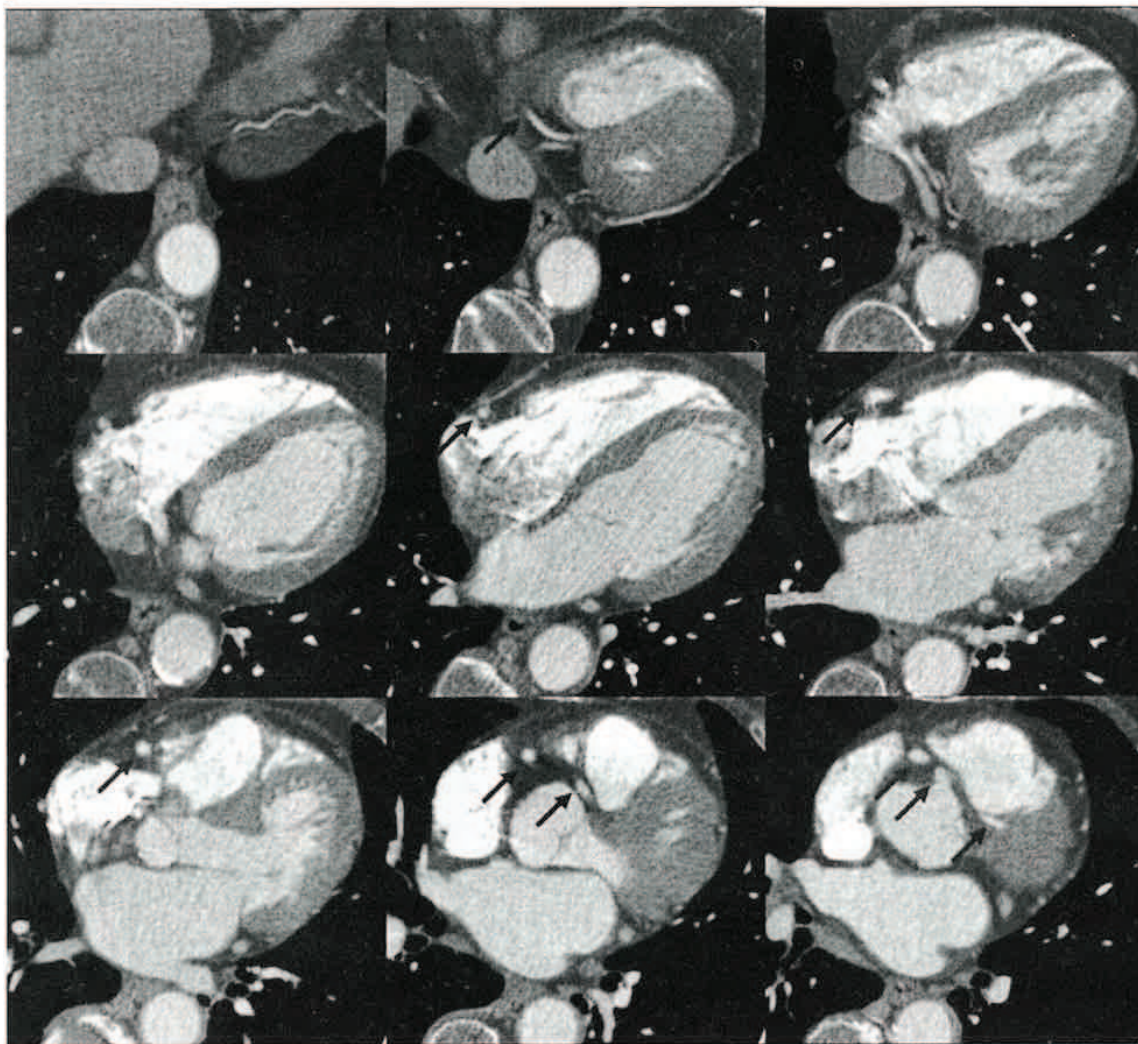


FIG. 14. Kymogram-based ASSR CI reconstruction of 12-slice cardiac CT data. The images are spaced by 9 mm in caudo-cranial order from top left to bottom right. Arrows point at the right coronary artery which can be depicted clearly and at full length.

Figure 11 shows the ECG-correlated and the kymogram-correlated reconstructions together with the COM plots and the kymogram functions. Image quality of both approaches appears to be the same although some discontinuities in the MPR displays differ. The kymogram functions x_{buc} , y_{buc} , and x'_{buc} nicely show the correlation of the cardiac anatomy and the amplitude of motion: the aortic motion alone yields a lower amplitude of the COM motion than the motion of the ventricles. The lag function is almost horizontal and indicates a good correlation between ECG and kymogram.

Another patient is shown in Fig. 12 which compares standard, ECG-correlated and kymogram-correlated reconstructions. Both the ECG-correlated and the kymogram-correlated reconstruction are, not surprising, clearly superior to the standard approach although substantial motion artifacts still remain for certain heart beats. Apart from slightly fewer discontinuities in the kymogram reconstruction the two phase-

correlated reconstructions yield comparable image quality. Please note, the kymogram-based reconstruction and the standard reconstruction are both based on the same prerequisites: A standard CT scan without additional ECG acquisition. The improvement in image quality, however, is significant.

For a few patient cases, the ECG signal may be defective or the ECG monitor's *R*-peak detection algorithms may fail. In the case presented in Fig. 13, the *R*-peak detection did not only detect the *R* waves but also the *T* waves—the *T* wave typically appears less pronounced than the *R* wave—of the patient. Therefore, the patient's heart rate appeared to be twice as high. Since the ECG file was not corrupt, this error remained unnoticed during ECG-correlated reconstruction. The kymogram, in contrast, detected the cardiac motion correctly. Results are shown in Fig. 13. The phase lag is strongly increasing since the ECG signal reports a twofold increase of

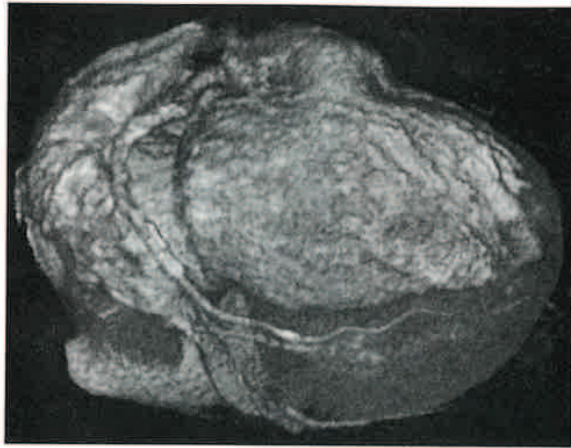


FIG. 15. Kymogram-based ASSR CI reconstruction of 12-slice cardiac CT data viewed from anterior/caudal using volume rendering. The coronary arteries are nicely depicted at full length.

the cardiac phase as compared to the kymogram signal. Close to the scan end the ECG monitor started to detect correctly and, consequently, the lag function turns into a horizontal line. Figures 13(b) and 13(c) show the ECG correlated and the kymogram-correlated reconstructions of a single slice for the phases (ECG and kymogram) 10%, 30%, 50%, 70%, and 90%. Whereas the kymogram-correlated reconstruction depicts the heart in a full cycle of motion, the ECG-correlated images appear to be mixed and, even more drastically, the artifact content is increased due to overlapping structures. This can be explained by the fact that the reconstruction algorithm, based on the false ECG interpretation, combines data segments corresponding to different (true) heart phases. Figure 5 shows the windowed Fourier transform of that patient; the true heart rate between 60 min^{-1} and 70 min^{-1} can be clearly seen from this density plot.

As a further demonstration Fig. 14 gives an impression of the kymogram performance on 12-slice cone-beam CT with a rotation time of 0.42 s. Unfortunately, we have no ECG available with our CBCT scanner and cannot compare the image quality of kymogram-correlated CBCT to ECG-correlated CBCT. Nevertheless, the high quality of the transaxial reconstruction and the high quality of the volume rendering in Fig. 15 indicate a good correlation of the kymogram and the cardiac motion also for cone-beam CT data.

D. Statistical evaluation

To quantify the kymogram algorithm in comparison to the ECG signal we performed a statistical evaluation of the lag function for 25 consecutive cardiac patients. First, the z positions that did not cover the heart were excluded from the data. Then, the mean and the standard deviation of the lag function's values were computed. The mean values are equivalent to the offset Δc_E introduced in Sec. III B 4. The

TABLE I. Patient mean heart rate, mean lag offset Δc_E and lag function variation σ_{L_E} in relation to the gold standard ECG. The last two lines show the mean and standard deviation over the respective columns. (Patient 7 was excluded because of disturbed ECG data.)

Patient	f_H (ECG)	f_H (Kymo)	Δc_E	σ_{L_E}
1	75 min^{-1}	75 min^{-1}	5%	3.05%
2	64 min^{-1}	64 min^{-1}	1%	1.38%
3	69 min^{-1}	69 min^{-1}	55%	5.45%
4	89 min^{-1}	87 min^{-1}	4%	7.51%
5	75 min^{-1}	75 min^{-1}	97%	1.46%
6	70 min^{-1}	70 min^{-1}	1%	3.19%
7	***	68 min^{-1}	***	***
8	70 min^{-1}	69 min^{-1}	3%	4.40%
9	54 min^{-1}	54 min^{-1}	41%	2.20%
10	101 min^{-1}	101 min^{-1}	53%	24.5 %
11	87 min^{-1}	87 min^{-1}	15%	3.08%
12	79 min^{-1}	79 min^{-1}	30%	2.75%
13	61 min^{-1}	61 min^{-1}	38%	4.84%
14	64 min^{-1}	64 min^{-1}	93%	4.65%
15	66 min^{-1}	66 min^{-1}	49%	1.25%
16	69 min^{-1}	69 min^{-1}	2%	2.52%
17	67 min^{-1}	67 min^{-1}	97%	1.45%
18	75 min^{-1}	74 min^{-1}	97%	2.18%
19	65 min^{-1}	65 min^{-1}	94%	4.65%
20	52 min^{-1}	52 min^{-1}	29%	2.72%
21	84 min^{-1}	84 min^{-1}	2%	2.11%
22	70 min^{-1}	71 min^{-1}	47%	3.75%
23	78 min^{-1}	78 min^{-1}	2%	2.13%
24	61 min^{-1}	61 min^{-1}	39%	4.15%
25	97 min^{-1}	97 min^{-1}	2%	8.81%
mean:	73 min^{-1}	73 min^{-1}	***	4.53%
sigma:	13 min^{-1}	13 min^{-1}	***	4.85%

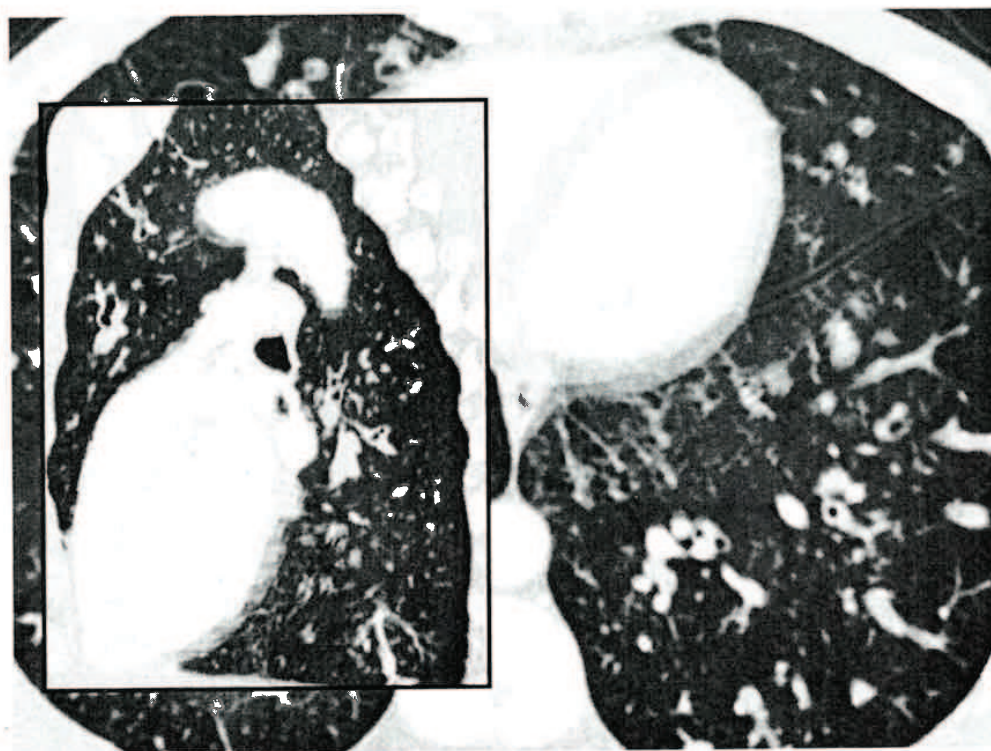
standard deviation σ_{L_E} is a measure of the kymogram quality if one assumes the ECG to be the gold standard for cardiac motion synchronization. Results of our analysis are given in Table I. Please note that only 4-slice data enter this table since we have no ECG available for the cone-beam scans.

The table shows a good match between the ECG and the kymogram. The deviation of the lag function is below 5% in 84% of all cases. This is also indicated by the good agreement in detected heart rate. As patients 10 and 25 indicate, the kymogram tends to match the ECG less closely for higher heart rates.

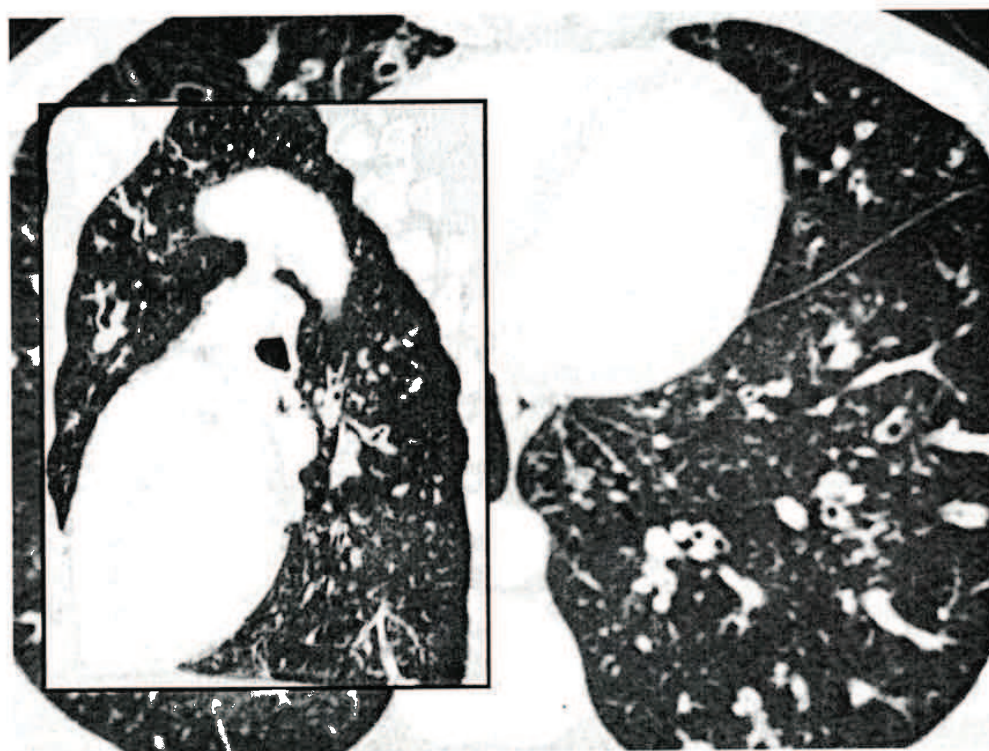
VI. DISCUSSION AND CONCLUSIONS

The kymogram approach as presented in this paper involves a number of ad hoc steps, such as data windowing and filtering, that are not strictly derived from theory. However, experience has shown that these steps are necessary. This fact and the overall results obtained justify our procedure.

In general, it has turned out that information nearly equivalent to the ECG's phase information can be obtained from the raw data at the level of the heart; slight deteriorations for heart rates that approach the scanner's resonance frequency have been observed. Regarding that the improvements in image quality obtained with the kymogram compared to standard reconstructions are equivalent to the im-



a) ASSR Std reconstruction



b) Kymogram-correlated ASSR CI reconstruction

FIG. 16. Improvements that can be obtained for a standard thorax scan when using kymogram-correlated reconstruction.

provements obtained by reconstructing ECG-correlated, which were the basis for modern cardiac CT,² is highly impressive and should stimulate further research on motion-correlated reconstruction.

Although the studies have been presented mainly for $t_{\text{rot}} = 0.5$ s, there is no loss of generality since our results scale according to the rotation time of the scanner. Assume a scanner with t'_{rot} , then the results must be simply scaled according to $f'_H = f_H t_{\text{rot}} / t'_{\text{rot}}$. Consequently, CT scanners with shorter rotation times allow us to detect cardiac motion for heart rates above 120 min^{-1} as well. This is the case with our CBCT scanner that shows the resonance at 143 min^{-1} .

For most cases, comparable image quality has been achieved with both phase-correlated approaches. There may be cases (that have not occurred in our study) where the kymogram approach fails due to severe arrhythmia of the patient which would violate the assumption of slowly varying heart rate. But there are also cases where the kymogram is superior to the ECG. In particular, the case of misinterpreted *T* waves which happened in one of 25 consecutive cardiac patients yielded superior images with the kymogram approach and where the kymogram gave the hint for detecting the ECG monitor's failure.

To summarize, the novel approach of motion detection appears to be a viable alternative to ECG-based reconstruction. It is possible to use the kymogram to substitute the ECG information but it also seems of high value to have both approaches available since potential errors (that may occur for the ECG but also for the kymogram) may be compensated thus improving the overall image quality. A potential disadvantage is that the kymogram cannot be used for prospective triggering or dose modulation. Prospective methods require the prediction of cardiac motion at least 180° in advance and the kymogram algorithm consists of signal processing steps that involve more than 720° of data. Hence, the kymogram detection is not as localized as a prospective operation would require.

An important additional point is that the kymogram technique may be useful for thoracic and lung imaging since it allows for motion compensation not only in the heart but also in pericardial lung regions which often suffer from blurring of diagnostically important details. To fortify this suggestion we have used *standard* thorax data with 0.5 s rotation and with a pitch of 0.5 acquired with a 16-slice CT scanner to perform both a standard and a kymogram-based ASSR CI reconstruction. The significant improvements obtained with the new method are demonstrated in Fig. 16. A pitch value lower than one is the only precondition that must be satisfied

for this lung imaging technique. Due to the high volume coverage of modern cone-beam scanners this means no restriction to clinical routine.

ACKNOWLEDGMENTS

This work was supported by grant AZ 262/98 by "Bayerische Forschungsförderung, D-80333 München, Germany." We thank Dr. Stephan Achenbach, Dr. Ulrich Baum, Dr. Michael Lell, and Dr. Dieter Ropers who carried out the patient studies for a very efficient and pleasant cooperation.

^aElectronic mail: marc.kachelriess@imp.uni-erlangen.de

¹W. Stanford, B. H. Thompson, and R. M. Weiss, "Coronary artery calcification: Clinical significance and current methods of detection," *Am. J. Roentgenol.* **161**, 1139–1146 (1993).

²M. Kachelrieß and Willi A. Kalender, "Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart," *Med. Phys.* **25**, 2417–2431 (1998).

³M. Kachelrieß, S. Ulzheimer, and W. A. Kalender, "ECG-correlated image reconstruction from subsecond multi-slice spiral CT scans of the heart," *Med. Phys.* **27**, 1881–1902 (2000).

⁴M. Kachelrieß, S. Ulzheimer, and W. A. Kalender, "ECG-correlated imaging of the heart with subsecond multislice CT," *IEEE Trans. Med. Imaging* **19**, 888–901 (2000).

⁵B. Ohnesorge, T. Flohr, C. Becker, A. Kopp, U. Schöpf, U. Baum, A. Knez, K. Klingenberg-Regn, and M. Reiser, "Cardiac imaging by means of electrocardiographically gated multisection spiral CT: initial experience," *Radiology* **217**, 564–571 (2000).

⁶S. Ulzheimer, Ph.D. thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg, 2001.

⁷T. Pan and S. Yun, "Cardiac CT with variable gantry speeds and multi-sector reconstruction," *Radiology* **217**, 438 (2000).

⁸T. Flohr, B. Ohnesorge, C. Becker, A. Kopp, S. Halliburton, and A. Knez, "A reconstruction concept for ECG-gated multi-slice spiral CT of the heart with pulse-rate adaptive optimization of spatial and temporal resolution," *Radiology* **217**, 438 (2000).

⁹M. Kachelrieß and W. Kalender, "Computertomograph mit objektbezogener Bewegungsartefaktreduktion und Extraktion der Objektbewegungsinformation (Kymogramm)," European Patent Office, 1999, Patent Specification EP 1 061 474 A1.

¹⁰S. Achenbach, U. Baum, S. Ulzheimer, M. Kachelrieß, D. Ropers, T. Giesler, W. Bautz, W. G. Daniel, W. A. Kalender, and W. Moshage, "Visualization of the coronary artery lumen by contrast-enhanced multi-detector spiral CT with retrospective ECG gating," *Circulation* **102**, II–398 (2000).

¹¹S. Achenbach, S. Ulzheimer, U. Baum, M. Kachelrieß, D. Ropers, T. Giesler, W. Bautz, W. G. Daniel, W. A. Kalender, and W. Moshage, "Noninvasive coronary angiography by retrospectively ECG-gated multislice spiral CT," *Circulation* **102**, 2823–2828 (2000).

¹²M. Kachelrieß, T. Fuchs, R. Lapp, D. Alexander Sennst, S. Schaller, and W. Kalender, "Image to volume weighting generalized ASSR for arbitrary pitch 3D and phase-correlated 4D spiral cone-beam CT reconstruction," *Proceeding of the 6th International Meeting on Fully 3D Image Reconstruction*, pp. 179–182, 2001.

¹³S. G. Azevedo, D. J. Schneberk, P. J. Fitch, and H. E. Martz, "Calculation of the rotational centers in computed tomography sinograms," *IEEE Trans. Nucl. Sci.* **37**, 1525–1540 (1990).



Journals, Magazines, Newspapers

Medical physics

AVAILABLE AS

Online

Physical



View Online



Available Issues / Request a Copy

” Citation

Details

Physical Locations



This item is also held by UW-Eau Claire, UW-La Crosse, and UW-Milwaukee



Multiple items exist. Use [Available Issues / Request a Copy](#) to see what's on the shelf.

Ebling Library

Today's hours: 9 a.m.–5 p.m.

Stacks

Q 7M4613 P5

This Location Has

v.42(2015)-v.43(2016)

Middleton Shelving Facility**by request only**

Q 7M4613 P5 (23-D-6)

This Location Has

v.1(1974)-v.35(2008)

v.36:no.1(2009)-v.36:no.9(2009)

v.36:no.11(2009)-v.36:no.12(2009)

v.37(2010)-v.41(2014)

Indexes

v.1/10(1974/1983)

v.11/20(1984/1993)

Publication Details**FORMAT**

Journals, Magazines, Newspapers

LANGUAGE

English

CONTRIBUTORS[American Association of Physicists in Medicine](#)[American Institute of Physics](#)**PUBLICATION**

[New York, N.Y.] : Published for the American Association of Physicists in Medicine by the American Institute of Physics

PUBLICATION DATES

Vol. 1, no. 1 (1974)-

PHYSICAL DETAILS

volumes : illustrations ; 29 cm

ISSNS

0094-2405, 2473-4209

OCLC

ocm01794379, ocm45401920

PRECEDING TITLES

[Quarterly bulletin \(American Association of Physicists in Medicine\)](#)

Notes

Also available on the Internet.

Subjects

[Medical physics -- Periodicals.](#)

[Biophysics -- periodicals.](#)

Medical Subject Heading

Content Types

[Periodicals](#)

[periodicals](#)

Items Related By Call Number

[Shelf Browse](#)



**Journals, Magazines,
Newspape...**
Iranian journal of radiation
research : IJRR

R895.A1 I73

**Journals, Magazines,
Newspape...**
Journal of medical physics

Online
R895.A1 J68





Additional Information

Library Staff Details



Items Related By Call Number

[Shelf Browse](#)

Journals, Magazines, Newspaper...

Iranian journal of radiation research : IJRR

R895.A1 I73

Journals, Magazines, Newspaper...

Journal of medical physics

Online
R895.A1 J68

Journals, Magazines, Newspaper...

Journal of nuclear medicine technology

Online
Physical
R895.A1 J68

Journals, Magazines, Newspaper...

Journal of the American College of Radiology : JA...

Online
R895.A1 J685

Additional Information

Library Staff Details

MARC Bibliographic Record

LEADER	01337cas a2200409 a 4500		
001	991693373602122		
005	20150313115148.0		
008	741029c19749999nyubr1p	0uuua0eng	
010	\$a	74645246	
022	\$a	0094 - 2405	
030	\$a	MPHYA6	
035	\$a	(OCoLC)01794379	
035	\$9	AAT5586UW	
035	\$a	169337	
035	\$a	(WU)169337-uwmadisondb	
035	\$a	(EXLNZ-01UWI_NETWORK)999483150302121	
040	\$aDLC\$beng\$cDLC\$dNSD\$dDLC\$dOCL\$dNSD\$dm.c.\$dGZH		
042	\$a	lc\$ansdp	
050	00	\$aR895.A1\$bM44	
060	_0	\$aw1 ME409R	
082		\$a610/1/53	
210	0_	\$aMed Phys	

222	_0	\$aMedical physics\$b(Lancaster)
245	00	\$aMedical physics.
260		\$a[New York, N.Y.] :\$bPublished for the American Association of Physicists in Medicine by the American Association of Physicists in Medicine
300		\$avolumes :\$billustrations ;\$c29 cm
310		\$aBimonthly
336		\$atext\$btxt\$2rdacontent
337		\$aunmediated\$bn\$2rdamedia
338		\$avolume\$bnc\$2rdacarrier
362	0_	\$aVol. 1, no. 1 (1974)-
530		\$aAlso available on the Internet.
650	_0	\$aMedical physics\$vpPeriodicals.
650	_2	\$aBiophysics\$vpperiodicals.
710	2_	\$aAmerican Association of Physicists in Medicine.
710	2_	\$aAmerican Institute of Physics.
780	05	\$tQuarterly bulletin (American Association of Physicists in Medicine)\$x0001-0162
997		\$aMARCIVE
LEADER		02405cas a2200565 a 4500
001		991021973005802122
005		20241211213017.0
006		m o d
007		cr mnu
008		001120c19749999nyumr p o 0 a0eng c
010		\$a 2007233899
016	7_	\$a017845188\$2Uk
022		\$a2473-4209
035		\$a(DE-599)ZDB1466421-5
035		\$a(OCOLC)45401920
035		\$a(CONSER) 2007233899
035		\$a(CKB)954925464206
035		\$a(EXLCZ)99954925464206
040		\$aOH1\$beng\$cOH1\$dOCLCQ\$dTMC\$dOCLCQ\$dGUA\$dLLB\$dOCLCQ\$dPFM\$dOCLCF\$dOCLCQ\$dDLC\$dUAB\$dCOO\$dNRC\$dU3W\$dOCI
042		\$apcc\$ansdp
050	10	\$aISSN RECORD

050	14	\$aR895.A1
060	00	\$aW1\$bME409R
082	00	\$a610.153\$223
210	0_	\$aMed. phys.\$b(Lanc. Online)
222	_0	\$aMedical physics\$b(Lancaster. Online)
245	00	\$aMedical physics.
246	1_	\$aMedical physics online
260		\$a[Woodbury, N.Y.] :\$bAmerican Association of Physicists in Medicine [by the American Institute of Physics]
264	31	\$3<2017-> :\$aHoboken, NJ :\$bJohn Wiley & Sons
336		\$atext\$btxt\$2rdacontent
337		\$acomputer\$bc\$2rdamedia
338		\$aonline resource\$bcr\$2rdacarrier
362	1_	\$aBegan with vol. 1, no. 1 (Jan. 1974).
500		\$aRefereed/Peer-reviewed
588		\$aDescription based on first issue; title from pdf image of article (publisher's Web site, viewed Nov 13, 2016).
588		\$aLatest issue consulted: Volume 43, Issue 7 (July 2016) (AIP website, viewed July 13, 2016).
650	_0	\$aMedical physics\$vPeriodicals.
650	_2	\$aBiophysics.
650	_6	\$aPhysique médicale\$vPériodiques.
650	_7	\$aMedical physics.\$2fast\$0(OCOLC)fst01014499
650	17	\$aGeneeskunde.\$2gnt
650	17	\$aNatuurkunde.\$2gnt
650	17	\$aToepassingen.\$2gnt
655	_2	\$aPeriodical.
655	_7	\$aPeriodicals.\$2fast\$0(OCOLC)fst01411641
655	_7	\$aPeriodicals.\$2lcgft\$0https://id.loc.gov/authorities/genreForms/gf2014026139
776	08	\$x0094-2405
780	00	\$tQuarterly bulletin - American Association of Physicists in Medicine\$w(CKB)991042742884000\$w(DLC)991042742884000
710	2_	\$aAmerican Institute of Physics.
710	2_	\$aAmerican Association of Physicists in Medicine.
906		\$aJOURNAL

MMS IDs

Document ID: 999483150302121
Network Electronic IDs: 9911025287002121
Network Physical IDs: 999483150302121
mms_ec_ids: 993263983402134, 99925642879302134
mms_lc_ids: 992194863402125, 991016458918102125
mms_mad_ids: 991693373602122, 991021973005802122
mms_ml_ids: 99584513402124, 991012396505902124
mms_gb_ids: 991006764787202123
mms_osh_ids: 991004583909702126
mms_pl_ids: 99901306823502127
mms_rf_ids: 991014192921702129
mms_sf_ids: 991015036825102130
mms_st_ids: 991013926952302131
mms_ww_ids: 991015503953802133