

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

DENTAL IMAGING TECHNOLOGIES CORPORATION

Petitioner

v.

3SHAPE A/S

Patent Owner

U.S. Patent No. 10,695,151 to Fisker *et al.*

Issue Date: June 30, 2020

Title: DETECTING TOOTH SHADE

DECLARATION OF JAMES L. MULLINS, Ph.D.

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I. INTRODUCTION

1. I, James L. Mullins, hereby declare as follows:

2. I have been retained by Foley & Lardner LLP on behalf of Dental Imaging Technologies Corporation to authenticate and establish the dates of public accessibility of certain documents for use in inter partes review proceedings. For this service, I am being paid my usual hourly fee of \$275/hour. My compensation in no way depends on the substance of my testimony or the outcome of the proceedings.

3. I have personal knowledge of the facts and opinions set forth in this declaration, I believe them to be true, and if called upon to do so, I would testify competently to them. I have been warned that willful false statements and the like are punishable by fine or imprisonment, or both.

II. BACKGROUND AND QUALIFICATIONS

4. I am a retired academic librarian working as the Founder and Owner of the firm Prior Art Documentation Librarian Services, LLC at 205 St Cuthbert, Williamsburg, VA 23188. Attached as Attachment B is a true and correct copy of my Curriculum Vitae (“CV”) describing my background and experience. Further information about my firm, Prior Art Documentation Librarian Services, LLC (PADLS), is available at www.priorartdoclib.com.

5. In forming the opinions expressed in this Declaration, I have considered and relied upon my background and experience. In addition, I have reviewed and

relied upon additional materials in preparation of this Declaration, as described below and provided in the Appendixes to this Declaration.

6. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus, Purdue University, 2018 – present.

7. I was previously employed as follows:

- Dean of Libraries and Professor & Esther Ellis Norton Professor, Purdue University, West Lafayette, IN, 2004-2017.
- Assistant/Associate Director for Administration, Massachusetts Institute of Technology (MIT), Cambridge, MA, 2000-2004.
- University Librarian and Director, Falvey Memorial Library, Villanova University, Villanova, PA, 1996-2000.
- Director of Library Services, Indiana University South Bend, South Bend, IN, 1978-1996.
- Part-time instructor, School of Library and Information Science, Indiana University, Bloomington, IN, 1979-1996.
- Associate Law Librarian, and associated titles, Indiana University School of Law, Bloomington, IN, 1974-1978.
- Catalog Librarian, Assistant Professor, Georgia Southern College (now University), Statesboro, GA, 1973-1974.

8. Over the course of my career as a librarian, instructor of library science, author of scholarly publications, and presenter at national and international conferences, I have had experience with catalog records and online library management systems built around Machine-Readable Cataloging (MARC) standards.

9. In the course of more than forty-four years as an academic librarian and scholar, I have been an active researcher. In my years as a librarian, I have facilitated the research of faculty colleagues either directly or through the provision of and access to the requisite print and/or digital materials and services at the universities I worked. I have kept current on the professional library science literature and served on the editorial board of the most prominent library journal, *College and Research Libraries*. This followed service as the chair of the Research Committee of the Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA). As an academic library administrator, I have had responsibility to ensure that students were educated to identify, locate, assess and integrate information garnered from library resources.

III. PRELIMINARIES

10. I am not a lawyer, and I am not rendering an opinion on the legal question of whether a particular document is, or is not, a “printed publication” under the law.

11. I am, however, rendering my expert opinion on the authenticity of the document referenced herein and on when and how this 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 by at least February 7, 2013.

12. I am informed by counsel that an item is considered authentic if there is sufficient evidence to support a finding that the item is what it is claimed to be. I am also informed that authenticity can be established based on the contents of the documents themselves, such as the appearance, content, substance, internal patterns, or other distinctive characteristics of the item, taken together with all of the circumstances.

13. I am informed by counsel that a given reference is publicly accessible upon a satisfactory showing that such a document has been disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art exercising reasonable diligence, can locate it. I have also been informed by counsel that materials available in a library constitute printed publications if they are cataloged and indexed according to general library practices that make the references available to members of the interested public.

14. In forming the opinions expressed in this declaration I have reviewed the documents and appendices referenced herein. These materials are records created

in the ordinary course of business by publishers, libraries, indexing services, and others. From my years of experience, I am familiar with the process for creating many of these records, and I know these records are created by people with knowledge of the information in the record. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its appendices are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

15. I am told by counsel that the subject matter of this proceeding relates to methods for automating tooth shade determination by obtaining a three-dimensional (“3D”) representation of the tooth comprising both shape data and texture data.

16. I have been informed by counsel that a person of ordinary skill in the art at the time of the inventions 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.

17. I am told by counsel that persons of ordinary skill in the art (“POSA”) would have had a bachelor’s degree in Computer Engineering, Computer Science, Computer Vision, or an equivalent field, as well as at least two years of imaging/image analysis experience, or alternatively, at least five years of

comparable industry experience. A POSA would have had experience with and knowledge of 3D imaging systems and 3D modeling techniques.

18. It is my opinion that such a person would have been engaged in academic research, learning through study and practice in the field and possibly through formal instruction the bibliographic resources relevant to his or her research. In the 2010s such a person would have had access to a vast array of print resources in content-delivery and interface design in interactive computer networks as well as to a fast-changing set of online resources.

A. Library Records

19. Some background on MARC formatted records, OCLC, *WorldCat*, and OCLC's Connexion is needed to understand the library catalog records discussed in this declaration.

20. Libraries world-wide use the MARC format for catalog records; this machine-readable format was developed by the Library of Congress in the 1960s.

21. MARC formatted records provide a variety of subject access points based on the content of the document being cataloged. All subject headings may be found in the MARC fields 6XX. For example, MARC Field 600 identifies personal names used as subjects and the MARC Field 650 identifies topical terms. A researcher might discover material relevant to his or her topic by a search using the terms employed in the MARC Fields 6XX.

22. The MARC Field 040, subfield a, identifies the library or other entity that created the original catalog record for a given document and transcribed it into machine readable form. The MARC Field 008 identifies the date when this first catalog record was entered on the file. This date persists in all subsequent uses of the first catalog record, although newly-created records for the same document, separate from the original record will show a new date. It is not unusual to find multiple catalog records for the same document

23. *WorldCat* is the world's largest public online catalog, maintained by the Online Computer Library Center, Inc., or OCLC, and built with the records created by the thousands of libraries that are members of OCLC. *WorldCat* provides a user-friendly interface for the public to use MARC records; it requires no knowledge of MARC tags and codes. *WorldCat* is easily accessible through the World Wide Web to all who wish to search it; there are no restrictions to be a member of a particular community, etc. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed *WorldCat* records as the Date of Entry but not necessarily all.

24. Whereas *WorldCat* records are widely available, the availability of MARC formatted records varies from library to library.

25. When an OCLC participating institution acquires a document for which it finds no previously created record in OCLC, or when the institution chooses not

to use an existing record, it creates a record for the document using OCLC's Connexion, the bibliographic system used by catalogers to create MARC records. Connexion automatically supplies the date of record creation in the MARC Field 008.

26. Once the MARC record is created by a cataloger at an OCLC participating member institution, it becomes available to other OCLC participating members in Connexion and also in *WorldCat*, where persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, can locate it.

B. Periodicals

27. A library typically creates a catalog record for a periodical publication when the library receives its first issue. When the institution receives subsequent issues/volumes of the periodical, the issues/volumes are checked in (often using a date stamp), added to the institution's holding records, and made available very soon thereafter – normally within a few days of receipt or (at most) within a few weeks of receipt.

28. The initial periodicals record will sometimes not reflect all subsequent changes in publication details (including minor variations in title, frequency, etc.).

C. Cataloging/Indexing

29. 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. Date information for indexing entries is, however, often unavailable. This is especially true for online indices.

30. 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. 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.

D. Databases

31. ***PubMed.org*** - PubMed is a free resource supporting the search and retrieval of biomedical and life sciences literature with the aim of improving health—both globally and personally.

32. The PubMed database contains more than 34 million citations and abstracts of biomedical literature. It does not include full text journal articles; however, links to the full text are often present when available from other sources, such as the publisher's website or PubMed Central (PMC).

33. Available to the public online since 1996, PubMed was developed and is maintained by the National Center for Biotechnology Information (NCBI), at the U.S. National Library of Medicine (NLM), located at the National Institutes of Health (NIH). <https://pubmed.ncbi.nlm.nih.gov/about/>.

IV. OPINION REGARDING CHU

34. I have been asked to opine on the authenticity and public access of an article authored by Stephen J. Chu et al., “Dental Color Matching Instruments and Systems. Review of Clinical and Research Aspects,” published in the *Journal of Dentistry*, Volume 38, December 2010, Supplement 2, pp. e2-e16 (“Chu”).

35. For consistency and clarification, Chu, when used in this declaration, refers not only to the Chu article but also the journal volume and issue in which it was published: *Journal of Dentistry*, Volume 38, December 2010.

A. Authentication

36. I have evaluated the authenticity of the Chu by assessing and reviewing the version of Chu provided to me by counsel (Exhibit 1106); and by accessing and assessing a download made of Chu for me from the Purdue University Libraries Document Delivery Services on September 13, 2022, from the Elsevier *Science Direct* database, Attachment A-1. Chu was only published in the digital format, so there is no print copy available in an academic/research library to confirm date of receipt.

37. Attachment A-1 was provided to me at my request on September 13, 2022, by Purdue University Libraries Document Delivery Services. Attachment A-1 includes a download of the Chu article. Chu is available as an open access document at this URL through Dental XP: <https://www.dentalxp.com/content/1863/8c629565-70a7-4c79-97a3-86b5e7206825.pdf>. Or for a fee through this URL: <https://www.sciencedirect.com/science/article/abs/pii/S0300571210001685>.

38. Based on obtaining Chu as a digital document from the Elsevier Science Direct database through the Purdue University Libraries Document Delivery Services, I conclude that Attachment A-1 is an authentic and accurate copy of Chu. I then compared Attachment A-1 to EX1106, provided by counsel, and I found no difference.

39. Therefore, I conclude and affirm that Chu is an authentic document.

B. Public Accessibility

40. Attachment A-2 is a download from PubMed.gov that I made on September 9, 2022. Chu could have been located on PubMed.gov, by completing a search by author: Stephen J. Chu; by title: “Dental Color Matching Instruments and Systems. Review of Clinical and Research Aspects”: and/or by subject headings (MeSH terms): *Color/standards; Colometry/instrumentation; Colorimetry/methods; Dental Prosthesis Design/methods; Dental Restoration, Permanent/methods; Esthetics, Dental, Humans; Prosthesis Coloring/Instrumentation; Prosthesis Coloring/methods; Spectrophotometry/Instrumentation; Tooth/anatomy & histology; Tooth discoloration/diagnosis and/or Tooth discoloration/Therapy.*

41. Anyone who had access to the Internet would have been able to query PubMed.gov and located and found the citation to Chu.

42. Since there was no print version of Chu, there are other means to prove public accessibility, such as by showing that Chu was actually cited in papers presented at a conference or cited in articles published in research journals. This supports public availability as it documents that other researchers had, in fact, accessed Chu. To ascertain whether others had cited Chu, I performed a search on *Google Scholar*. Below are three citations to Chu.

43. Attachment A-3 is an article by Ahmed, H. M. A., and P. V. Abbott, with the title: “Discolouration potential of endodontic procedures and materials: a review,” published in *International Endodontic Journal*, volume 45, number 10, in 2012 on pages 883-897 (“Ahmed”).

44. I downloaded Ahmed on September 3, 2022 through this open access URL: <https://onlinelibrary.wiley.com/doi/pdfdirect/10.1111/j.1365-2591.2012.02071.x>.

45. In “References” on page 895, Ahmed cites Chu in alphabetical order as shown below:

Chu SJ, Trushkowsky RD, Paravina RD (2010) Dental color matching instruments and systems. Review of clinical and research aspects. *Journal of Dentistry* 38(Suppl 2), e2–16.

46. Attachment A-4 is an article by Siegbert Witkowski, et al., with the title "Reliability of Shade Selection Using an Intraoral Spectrophotometer, published in *Clinical Oral Investigations*, volume 16, number 3, 2012 on pages 945-949. (“Witkowski”).

47. I downloaded Witkowski, Attachment A-4, on September 3, 2022, by my emeritus faculty status at Purdue University through this URL: [https://link-springer-com.ezproxy.lib.purdue.edu/content/pdf/10.1007/s00784-011-0590-3.pdf](https://link.springer-com.ezproxy.lib.purdue.edu/content/pdf/10.1007/s00784-011-0590-3.pdf). Witkowski is available for a fee at this URL: <https://link.springer.com/content/pdf/10.1007/s00784-011-0590-3.pdf>.

48. In “References” on page 949, Witkowski cites Chu as reference number 12, as shown below:

12. Chu SJ, Trushkowsky RD, Paravina RD (2010) Dental color matching instruments and systems. Review of clinical and research aspects. J Dent 38(Suppl 2):e2–e16

49. Attachment A-5 is an article by V. Cioban, et al., “Image Calibration for Color Comparison,” *Proceedings of 2012 IEEE International Conference on Automation, Quality and Testing, Robotics*, 2012, pp. 332-336. (“Cioban”)

50. I downloaded Cioban, Attachment A-5, on September 3, 2022, by my emeritus faculty status at Purdue University through this URL: <https://ieeexplore-ieee-org.ezproxy.lib.purdue.edu/stamp/stamp.jsp?tp=&arnumber=6237727>.

51. Cioban is available for a fee at this URL: <https://ieeexplore.ieee.org/abstract/document/6237727>.

52. In “References” on page e36, Cioban cites Chu as reference number [2], as shown below:

[2] Chu SJ, Trushkowsky RD, Paravina RD. *Dental color matching instruments and systems*. Review of clinical and research aspects. J Dent. 2010;38 Suppl 2:e2-16. Epub 2010 Aug

53. Chu would accordingly have been publicly accessible through *PubMed.org* as shown above.

54. Further evidence of public access to Chu are three citations to Chu in Ahmed, Attachment A-3; Witkowski, Attachment A-4; and Cioban, Attachment A-5.

55. Ahmed, Witkowski, and Cioban were all published in 2012, therefore, Chu was publicly accessible and known in 2012.

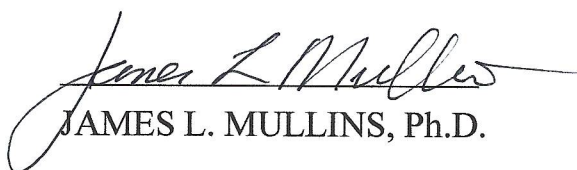
56. I conclude that Chu, EX1106, is an authentic document and would have been publicly accessible no later than February 7, 2013.

V. CONCLUSION

57. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner or its expert(s) may raise and to take-into account new information as it becomes available to me.

I hereby declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct, and that all statements made of my own knowledge are true and that all statements made on information and belief are believed to be true. I understand that willful false statements and the like are punishable by fine or imprisonment, or both (18 U.S.C. § 1001).

Executed on October 27, 2022 in Williamsburg, Virginia.


JAMES L. MULLINS, Ph.D.

Attachment A-1

available at www.sciencedirect.comjournal homepage: www.intl.elsevierhealth.com/journals/jden

Review

Dental color matching instruments and systems. Review of clinical and research aspects

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ABSTRACT

Objectives: To review current status of hand held systems for tooth color matching in vivo and corresponding research.

Sources: “Medline” database from 1981 to 2010 were searched electronically with key words tooth, teeth, color and dentistry.

Conclusion: Spectrophotometers, colorimeters and imaging systems are useful and relevant tools for tooth color measurement and analysis, and for quality control of color reproduction. Different measurement devices either measure the complete tooth surface providing a “color map” or an “average” color of the limited area [3–5 mm] on the tooth surface. These instruments are useful tools in color analysis for direct or indirect restorations, communication for indirect restorations, reproduction and verification of shade. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

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1. Introduction

The interest in color research in dentistry has increased significantly over the past several decades. When keywords color and dentistry were used for Medline search, only 107 papers were found by 1970. In subsequent decades, the number of references increased as follows: 409 (1980), 1134 (1990), 2259 (2000) and 4062 (April 2010). Advancements in technology, computers, the Internet, and communication systems have greatly affected and shaped modern society. Commensurate with these strides are the advancements in contemporary dentistry. During the past half decade, the

dental profession has experienced the growth of a new generation of technologies devoted to the analysis, communication and verification of shade. Shade determination for direct and indirect restorations has always been a challenge for the esthetic dentist. Clark in 1931 described this in the Color Problems in Dentistry.¹ As opposed to subjective visual shade selection with not always quite controlled conditions and methods, and shade guides that exhibited significant shortcomings, several authors tried to objectively quantify tooth color in the past. This was done through identifying color problems in dentistry²; the importance of the quantity and quality of light required to properly analyse shade³

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through studying correlation between extracted teeth and shade guides⁴ or the development of the early shade measuring instruments and shade guides.⁵

The late 1990s marked the birth of a new industry in dentistry, commercially available instrument-based color measurement systems, with the development of the ShadeScan system (Cortex Machina, Montreal, Canada).⁶ This was the first effort toward a shade analysis system for complete tooth surface measurement. Prior literature published by several authors described limited area measurement instruments, with an optical diameter of 3–5 mm, in the analysis of shade.^{7–9} Another study evaluated clinical application of the ShadeScan prototype which employed digital camera technology, in a case report comparing visual vs. instrument-based shade information in the restoration of a single maxillary central incisor.¹⁰

Today's shade-matching technologies have been developed in an effort to increase the success of color matching, communication, reproduction and verification in clinical dentistry, and, ultimately, to increase the efficiency of esthetic restorative work within any practice. The aim of this paper is to provide a comprehensive review of the current state of shade-matching technologies and instrumentation, and their clinical and research application.

2. Rationale

Dental shade-matching instruments have been brought to market to reduce or overcome imperfections and inconsistencies of traditional shade matching. The most commonly used shade-matching method is the visual method, whilst Vitapan Classical (Vita Zahnfabrik, Bad Säckingen, Germany) and its derivations are probably the most commonly used shade guides. The colored tabs of distinctive shades organize the empiric-based Vita chart.^{11–14} In addition, unequivocal findings were reported on color consistency amongst shade guides from the same manufacturer.^{15,16} Introduction of evidence-based Vitapan 3D-Master shade guides, Toothguide, Bleachedguide and particularly Linearguide by the same manufacturer correspond to color of human teeth and therefore increase chances for successful shade matching.^{17,18}

Historically, assessing shade visually has been characterized by several innate difficulties: metamerism, suboptimal color matching conditions, tools and method as well as the receiver's age fatigue, mood and drugs/medications.¹⁹ Despite these difficulties, the human eye can discern very small

differences in color. However, the ability to communicate the degree and nature of these differences is lacking.

The final color of an all-ceramic restoration is a merging of the underlying tooth structure or core and the ceramic material. The color of the final restoration cannot match the shade selected from a shade guide unless this modification is taken into account. Therefore, a stump or base tooth preparation shade needs to be obtained and transmitted to the technician.²⁰

3. Overview

Instruments for clinical shade-matching encompass spectrophotometers, colorimeters and imaging systems. As with any device, benefits and limitations exist, and the clinician must consider how the technology relates to expectations and needs. Intra-oral color measuring devices have been designed to primarily fit the needs of clinical dentistry, such as information on the corresponding shade tabs, tooth translucency, or information associated with color communication, reproduction and verification. This, together with price limitation dictated by the dental market, resulted in having scientific aspects, such as providing reflectance values or color formulation, less emphasized. Another significant difference compared to other, non-dental applications, are optical properties of human teeth—they are small, curved, multi-layered, translucent and exhibit color transitions in all directions (gingival to incisal, mesial to distal and labial to lingual). This is why the accurate repositioning (measurement of the same area) is frequently of critical importance for either clinical and research use of dental color matching devices. The list of instruments and software for in vivo color matching and their properties is given in Table 1.²¹

In addition to the instruments listed in Table 1, there are numerous dental color matching products that are presently withdrawn from the market, of limited availability, or undergoing major redesigning. The list includes Chromascan (Sterngold, Stamford, CT, USA), Dental Color Analyzer (Wolf Industries, Vancouver, Canada), Identacolor II (Identa, Holbaek, Denmark), Digital Shade Guide DSG4 (A. Reith, Schorn-dorf, Germany), Ikam (Metalor Technologies, Attleboro, MA, USA), ShadeEye NCC Chroma Meter (Shofu Dental, Menlo Park, CA, USA), Beyond Insight Shade Taking Device (Beyond Dental & Health, Beijing, China), Shadescan (Cynovad, Montreal, Canada) and Vita Easyshade (Vita Zahnfabrik, Bad Säckingen, Germany).

Table 1 – Instruments and software for color matching in dentistry: types, measurement area and relative cost (\$1000–\$7500).²¹

Product	Manufacturer	Device type	Measurement area	Relative cost
ClearMatch	Clarity Dental, Salt Lake City, UT	Software, digital image analysis	Complete tooth image	Low
CrystalEye	Olympus America, Center Valley, PA	Imaging Spectrophotometer	Complete tooth image	High
Easyshade Compact	Vident, Brea, CA	Spectrophotometer	5-mm probe diameter	Low
Shade-X	X-Rite, Grandville, MI	Spectrophotometer	3-mm probe diameter	Low
ShadeVision	X-Rite, Grandville, MI	Imaging colorimeter	Complete tooth image	Moderate
SpectroShade Micro	MHT, Niederhasli, Switzerland	Imaging Spectrophotometer	Complete tooth image	Moderate

4. Characteristics and clinical application

4.1. Spectrophotometers

Spectrophotometers are amongst the most accurate, useful and flexible instruments for overall color matching and color matching in dentistry.²² They measure the amount of light energy reflected from an object at 1–25 nm intervals along the visible spectrum.^{23,24} A spectrophotometer contains a source of optical radiation, a means of dispersing light, an optical system for measuring, a detector and a means of converting light obtained to a signal that can be analysed. The data obtained from spectrophotometers must be manipulated and translated into a form useful for dental professionals. The measurements obtained by the instruments are frequently keyed to dental shade guides and converted to shade tab equivalent.²⁵ Compared with observations by the human eye, or conventional techniques, it was found that spectrophotometers offered a 33% increase in accuracy and a more objective match in 93.3% of cases.²⁶

Crystaleye (Olympus, Tokyo, Japan) combines the benefits of a traditional spectrophotometer with digital photography. Through the development of optical and image processing technology, this product allows the practitioner to match tooth shade and color more accurately and simply compared with the traditional spectrophotometer.²⁷

The significant benefit of this system is that ‘virtual shade tabs’ in the computers database can be cross-referenced and superimposed visually onto the natural tooth image to be matched giving the technician the ability to visualize the correct shade tabs. The digital image produced by the Crystaleye uses a 7-band LED light source, which results in a more precise depiction of color than the conventional systems used with digital cameras. Moreover, the image produced by the Crystaleye is taken from inside the oral cavity and consequently is devoid of the external light that can cause discrepancies.

Vita Easyshade Compact (Vita Zahnfabrik, Bad Säckingen, Germany) is cordless, small, portable, cost efficient, battery operated, contact-type spectrophotometer that provides enough shade information to help aid in the color analysis process. Different measurement modes are possible with Easyshade Compact: tooth single mode, tooth area mode (cervical, middle and incisal shades), restoration color verification (includes lightness, chroma and hue comparison) and shade tab mode (practice/training mode).²⁸

Shade-X (X-Rite, Grandville, MI) is also compact and cordless “spot” measurement” spectrophotometer with 3-mm probe diameter, and keyed to the majority of popular shade guides. Shade-X have two databases to match the color of the dentin (more opaque) and the incisal tooth regions (more translucent).²⁹

SpectroShade Micro (MHT Optic Research, Niederhasli, Switzerland) is an imaging spectrophotometer. It uses a digital camera/LED spectrophotometer combination. It has an internal computer with the analytical software. The tooth positioning guidance system, shown on the LCD touch screen, is used during color measurement. Images and spectral data can be saved on the internal memory and transferred to a computer.³⁰

4.2. Colorimeters

Colorimeters measure tristimulus values and filter light in red, green and blue areas of the visible spectrum. Colorimeters are not registering spectral reflectance and can be less accurate than spectrophotometers (aging of the filters can additionally affect accuracy).³¹ ShadeVision (X-Rite, Grandville, MI) is an imaging colorimeter. Complete tooth image is provided through the use of three separate databases: for gingival, middle and incisal third. Virtual try-in feature enables virtual testing of color reproduction during fabrication.³²

4.3. Digital cameras and imaging systems

Digital Cameras. Most consumer video or digital still cameras acquire red, green and blue image information that is utilized to create a color image. The RGB color model is an additive model in which red, green and blue light are added together in various ways to reproduce a broad array of colors. Digital cameras represent the most basic approach to electronic shade taking, still requiring a certain degree of subjective shade selection with the human eye.³³ Various approaches have been used to translate this data into useful dental color information.

ClearMatch (Smart Technology, Hood River, OR) is a software system that uses high-resolution digital images and compares shades over the entire tooth with known reference shades.³⁰ Similar to the software associated with color measuring devices, ClearMatch contains the color database of industry-standard shade guides.³⁴

4.4. Interpretation and application of shade analysis data

Complete tooth surface measurement [CTSM] devices give a color map of the gingival, body and incisal shades for the fabrication of direct or indirect restorations. These systems give a virtual shade overlay of the proposed tab onto the digital image on the computer screen of the tooth measured for visual reference and assessment by the clinician and/or technician. CTSM spectrophotometers, such as Crystaleye and SpectroShade, provide shade tab designation and the respective ΔE^* values compared to shade tab values in the memory. However, these mappings are two dimensional and they do not necessarily take into account the shape, texture, thickness of the restoration, type of abutment and different core material (metal or ceramic).³⁵ In addition, they ‘average out’ color data over the complete tooth surface or larger defined areas which can lead to inaccurate shade information.

Limited area measurement devices provide 3–5 mm diameter areas of the tooth being measured. Therefore several areas of the tooth should be considered to obtain a representative evaluation of tooth shade. At a minimum, a limited area measurement of the gingival, body and incisal areas of the tooth [total of 3 measurements] should be assessed and recorded for the technician if an indirect restoration is prescribed. It was found that decreasing the window size when examining extracted teeth with a spectrophotometer and spectroradiometer resulted in lower CIE $L^*a^*b^*$ values.³⁶ Small-window tooth color measurement may cause edge loss of the light due to a tooth’s translucency.³⁷

Once the technology-based information is analysed, the information must be communicated to the technician for indirect restorations.³⁸ The aforementioned instruments and technologies are predominantly intended for shade analysis, however, this information alone may be insufficient for the technician to adequately interpret the shade information provided. Subsequent reference photography is highly recommended for communication on tooth color. Digital photographs are an important adjunct to the laboratory technician and together with the shade or “color map” should be sufficient communication material to construct an acceptable restoration.

Clinicians and technicians are frequently located in different areas. A digital camera permits the transfer of images from the clinician to the technician. The best way to reference shade information is by using shade tabs to communicate shade.³⁹ A systematic protocol to referencing shade information as well as changes in shade between tabs is required. Shades identified in the digital map are arranged by gingival (G), middle (M) and incisal third (I). The shade tabs should be selected and photographs should be taken with each tab in its proper orientation in reference to the tooth.

Camera and light settings and image format must be kept constant at all times for consistent shade color communication. In addition to the three basic shade tabs representing the respective G, M and I shades, two additional reference shade tab photographs should be included to graduate and calibrate shifts in hue, chroma and value between physical tabs visually in the laboratory, in the photographs and between the photos. One selected tab should be lighter in shade and one darker in shade in respect to the selected basic shades. The combination of accurate digital shade analysis information coupled with standardized reference shade communication photography can ensure a predictable esthetic restorative outcome of the final direct or indirect restoration.

Indirect restorations can and should be verified visually and with the instrument system in the laboratory prior to being returned to the clinician. This verification process can streamline wasteful chair side time attributed to remakes due to incorrect shade.^{40,41} Clinical excellence backed with sound color science and its appropriate interpretation can probably make the critical difference between good to excellent.⁴² Examples of color matching, interpretation and application of shade analysis data are given in Figs. 1–6.

5. Research

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. The most frequent research topics associated with these instruments and systems are associated with evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and evaluation on color compatibility, stability and interactions of human hard and soft oral tissues, head and neck tissues and dental materials. Although non-dental, professional bench-top color measurement instruments were used in many research projects in dentistry, this paper will focus mainly on these conducted using hand held devices designed for dental application.

5.1. Measurement uncertainties

In color science, evaluation of measurement uncertainties of shade-matching instruments is performed through precision and accuracy testing. The uncertainties associated with precision are most frequently associated with random errors, whilst the uncertainties associated with accuracy usually originate from systematic errors. Precision is tested by evaluation of repeatability (same method, operator or instrument) and reproducibility (different method, operator and/or instrument). Based on time interval, we are talking about short term (measurements in succession), medium term (hours) and long term measurements (weeks or longer). Based on the specimen manipulation, measurement can be performed with- and without replacement.⁴³ Evaluation of measurement uncertainties encompasses the use of referent instrument, preferably professional, non-dental, color measuring instrument.³⁷

In a study that compared five dental color measuring devices—ShadeScan, Easyshade, Ikam, IdentaColor II and ShadeEye, five group A Classical tabs were in vitro measured five times by two operators, whilst 25 upper right central incisors were measured in vivo by one operator. The best precision in vivo was recorded for Easyshade and Ikam, whilst performance of the other instruments was better in vitro than in vivo.¹² In an another study, SpectroShade, ShadeVision, VITA Easyshade and ShadeScan were evaluated.³¹ High reliability (reproducibility?) and variability in accuracy was reported. One in vitro study found that repeatability and accuracy of a dental color measuring instrument (ShadeScan) was influenced by shade guide systems used for testing.⁴⁴ When the precision of measurement of different tooth areas was evaluated, the middle third of each labial tooth surface exhibited the most consistent results.⁴⁵

Dental color matching instruments also provide the information on best matching tabs from different shade guides.^{25,46,47} This application-specific color information is also of importance and therefore requires proper attention of dental researches. When VITA EasyShade and ShadeEye NCC were tested on extracted human teeth, there were discrepancies in shade guide designations provided by the instruments. Higher inter-device agreement was recorded for Vitapan Classical than for Vitapan 3D-Master.²⁵

Digital imaging systems are becoming increasingly popular in determining the color of teeth. Precision and accuracy of these systems are influenced by the quality of camera and image processing method. Several studies reported that digital cameras, may be reliable instruments for determining the color of teeth and gingiva when combined with the appropriate calibration protocols.^{48–54}

Clinical imaging and conventional image processing methods such as Adobe Photoshop and Corel Photo-Paint are suitable for many purposes in dentistry: lab communication, documentation, patient education and others. However, scientific imaging,⁵⁵ appropriate methods of data processing and color science terminology is preferred in dental research. This, together with lack of the referent instrument (the instrument that has already been validated, not necessary by the same authors), diminished the validity of some studies on precision and accuracy of dental color matching instruments.

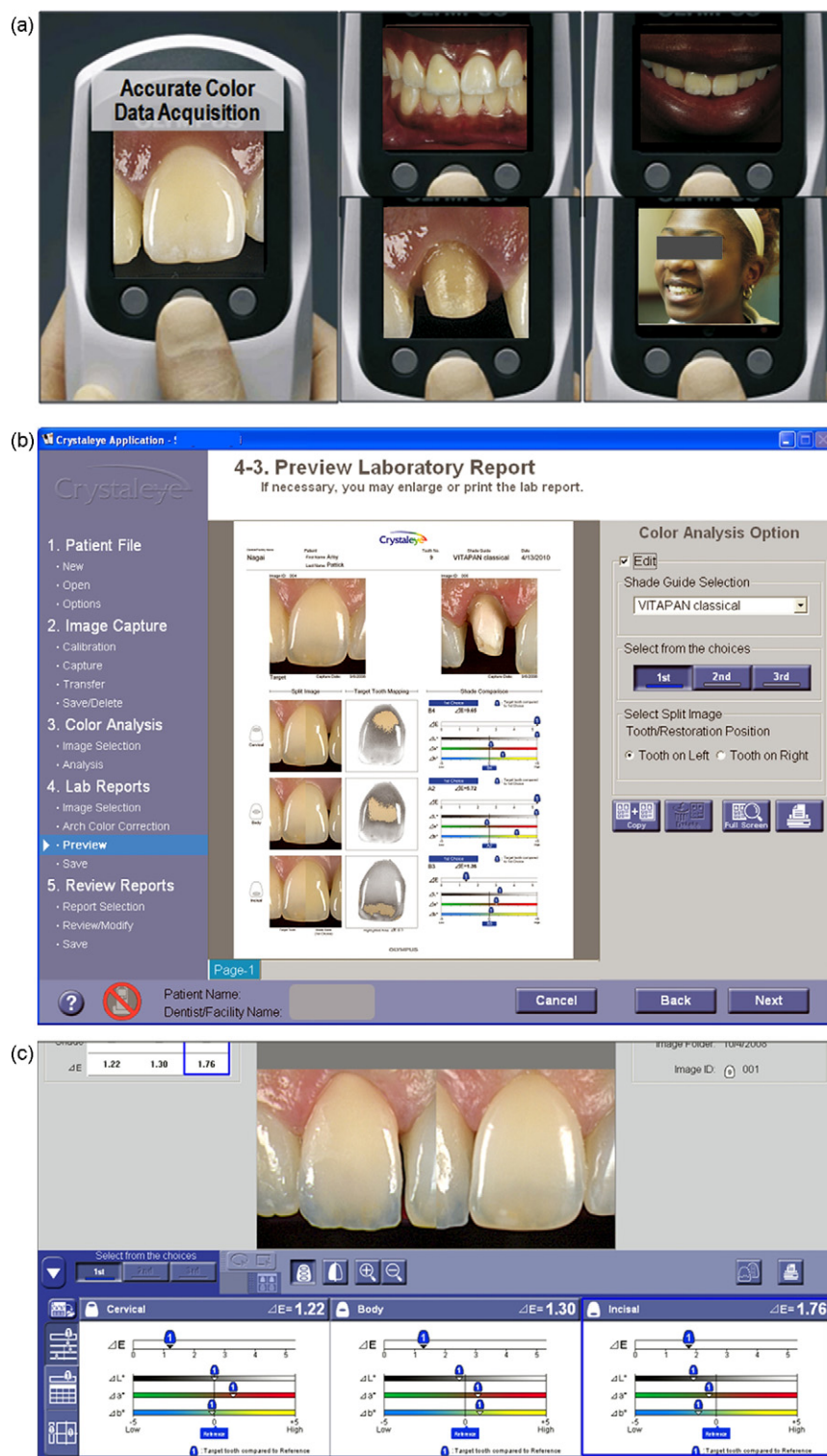


Fig. 1 – Clinical application of CrystalEye spectrophotometer (Courtesy Dr. Shigemi Nagai). (a) CrystalEye captures the spectral image of the tooth, abutment, arch and full face image. (b) Laboratory report can be sent to the lab as a quick color note. (c) Color analysis of the ceramic crown (after 1st bake try-in) placed on the abutment. Excellent color match was confirmed in the cervical and body areas. Minor modification may be required in the incisal area to increase the value and yellowness. (d) Color difference ΔE s obtained in all 3 areas are considered to be excellent color match. L^* value map indicates indistinguishable value distribution on #8 and #9.

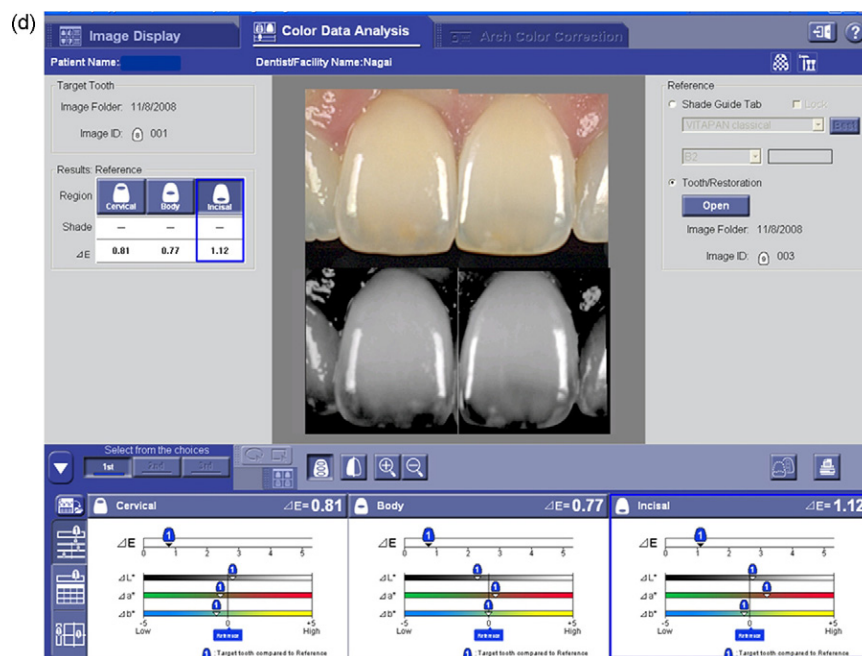


Fig. 1. (Continued).

5.2. Comparison between visual and instrumental findings

When the first dental color measuring instruments appeared, they exhibited slightly better accuracy compared to visual findings that were described as inconsistent.⁵⁶ Since that time, the modernization of both visual and instrumental means for color matching in dentistry occurred.^{17,57} More recently, better results were reported with dental spectrophotometer than using the visual method in approximately 47% of the cases,⁵⁸ which is in accordance with independent studies that documented the supremacy of spectrophotometric color matching compared to visual shade assessment.^{27,59} Another paper reported that the performance of Easyshade was comparable or better than that of dentists, whilst the agreement between visual and instrumental findings was qualified as good to very good.⁶⁰ In another paper, it was found that the agreement amongst the observer groups was significantly better than that of each device and that color matching instruments did not reflect human perception.⁶¹

It was found that consensus amongst observers led to better shade-matching results with some shade guides, compared to results of individual observers,⁶² and that intraexaminer shade-matching agreement was mainly acceptable.⁶³ Significantly higher visual-instrumental agreement was recorded for experienced dentists (compared to dental students and non-dental observers), regardless of shade guides and lighting conditions.⁶⁴

The comparison between visual and instrumental findings is a very attractive topic as it reveals pros and cons of both methods. Visual color matching is subjective and influenced by variety of factors. However, this method is not inferior and should not be underrated. Actually, the all “objective” color measuring instruments have been developed based on the

visual response of the “standard observer” and they are good only if they match that response. In addition, the numerically smallest ΔE^* value does not necessarily correspond to the best match because of the uneven eye sensitivity to hue, value and chroma differences. Therefore, the answer whether to use visual or instrumental method for color matching in dentistry is: whenever if possible, use both, as they complement each other and can lead towards predictable esthetic outcome.^{39–41}

5.3. Evaluation of visual color thresholds

Perceptibility and acceptability visual thresholds can be quantified only by combining visual and instrumental color measurement methods. Although majority of studies used professional (non-dental) color measuring devices in threshold evaluation, this topic is of exceptional importance in interpretation of color differences in clinical dentistry and dental research.

When the color difference between compared objects can be seen by 50% of observers (the other 50% will notice no difference), we are talking about the 50:50 perceptibility threshold.⁶⁵ When the color difference is considered acceptable 50% of observers (the other 50% would consider it unacceptable), this corresponds to 50:50 acceptability threshold. A color match in dentistry is a color difference at or below the former threshold, an acceptable color match is a color difference at or below the later one.⁶⁵

In dental literature, it is frequently interpreted that a ΔE^* of 1 is the 50:50 perceptibility threshold under controlled conditions (50% of observers will notice the color difference and 50% will see no difference between compared objects),⁶⁶ whereas a ΔE^* of 2.7⁶⁷ and 3.3⁶⁸ were found to be 50:50 acceptability thresholds (50% of observers will accept the restoration and 50% will replace it because of color mismatch).



Fig. 2 – Clinical application of EasyShade Compact spectrophotometer. (a) Instrument calibration. (b) Color measurement. (c) Color difference metric values as compared to the corresponding Vitapan Classical shade. (d) Color coordinate values and the corresponding Vitapan 3D-Master shade.

Several other studies, more or less controlled, reported the variability of findings on visual color thresholds.^{57,69–71} This, in addition to the introduction of new color difference formulae (CIEDE2000), suggests systematic approach and standardization of methods.

5.4. Color compatibility

Color compatibility studies encompass comparisons amongst teeth, shade guides and dental materials. Evaluation of color of natural teeth is important for clinical dentistry since knowledge on color ranges and color distribution of natural teeth can provide guidelines for designing of dental materials that will enable better and easier match to natural teeth.^{13,72} Databases encompassing spectral properties of teeth, regardless whether created using dental or non-dental color measuring devices, are of particular validity.⁷³ Two independent studies, both performed using Vita Easyshade, reported almost the same color coordinate ranges of natural teeth: $L^* = 55.5\text{--}89.6$ ⁷⁴ and $L^* = 58.7\text{--}88.7$ ⁷⁵; $a^* = 4.2\text{--}7.3$ ⁷⁴ and $a^* = 3.6\text{--}7.0$ ⁷⁵, and $b^* = 3.6\text{--}38.9$ ⁷⁴ and $b^* = 3.7\text{--}37.3$.⁷⁵ Current

shade guides exhibit moderate to pronounced discrepancy with results recorded for natural teeth. This discrepancy has been quantified by calculation of coverage error, the mean value of the minimal color differences amongst



Fig. 3 – Clinical application of Shade-X spectrophotometer.

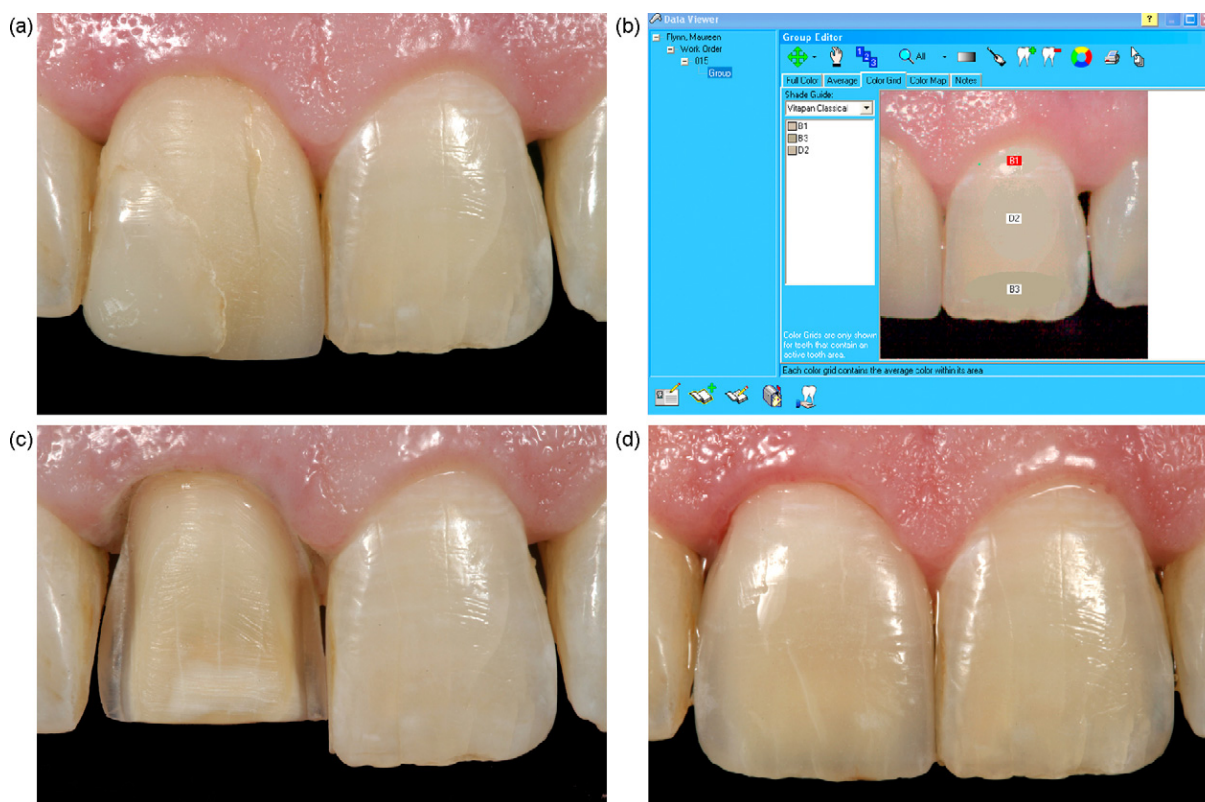


Fig. 4 – Clinical application of ShadeVision colorimeter. (a) The fractured veneer restoration on tooth #8 is to be replaced with a new veneer restoration. (b) The ShadeVision color mapping for tooth #9 to be matched with gingival, body and incisal shade reference tabs. (c) Veneer preparation tooth #8. It is important that an even thickness of tooth reduced is performed to insure color control of ceramic layering for predictable shade matching of the restoration. (d) Insertion of veneer restoration tooth #8 [Venus porcelain, Heraeus, Hanau, Germany] which matches the contralateral tooth satisfactorily and predictably without a remake.

each tab in the shade guide and the database of human teeth.^{17,73–76}

Although teeth exhibit color transitions in all directions, the correlation between colors of different regions on the labial tooth surface has been recorded. This study, performed using digital camera, suggested that color of a missing part of a tooth can be determined using the color of existing areas.⁷⁷ The same team reported color correlation between maxillary incisors and canines, which may influence color matching of missing teeth.⁷⁸

As far as the compatibility amongst materials is concerned, different comparisons have been performed. An Easyshade comparison between Vitapan Classical shade guide and four different veneering porcelain systems for metal ceramic restorations, revealed that differences were shade-dependent: A2 porcelain disks exhibited better match to corresponding VITA shade, followed by A3 and A3.5 disks.⁷⁹ The same instrument was used to test the ability of a ceramic system to correctly reproduce the shade selected using two shade guides. Toothguide 3D-Master outperformed VITA Classical.⁸⁰ When the quality of color match of different shade guides and corresponding porcelains was evaluated, the highest percentage of clinically acceptable matches was recorded for Toothguide 3-D Master/Omega 900 combination.⁸¹ A study, conducted using Easyshade,

reported that evaluated resin composites exhibited poor match compared to target Vitapan Classical tabs of the same shade designations.⁸² Similar conclusions were derived when various composites of corresponding shades were compared with a shade guide using a non-dental colorimeter,⁸³ and with each other using a bench-top spectrophotometer.⁸⁴

5.5. Color stability

Color stability of teeth and dental restoration is one of the prerequisites for long-lasting esthetics of dental restorations. Dental materials can exhibit color shifting during fabrication or at placement, and after placement. The later type of color shifting is associated with aging and staining.

When nanofill composite specimens were immersed into coffee, yerba mate, grape juice or water (control solution) for one week and tested using Easyshade, perceivable color change was observed only for the group immersed into the grape juice.⁸⁵ Another study used Easyshade to evaluate resin composites polished with two one-step polishing systems and exposed to coffee solution for seven days. Although all materials exhibited significant color changes, statistically significant polishing system-dependent differences were recorded ($p < 0.05$). Composite polymerized against Mylar

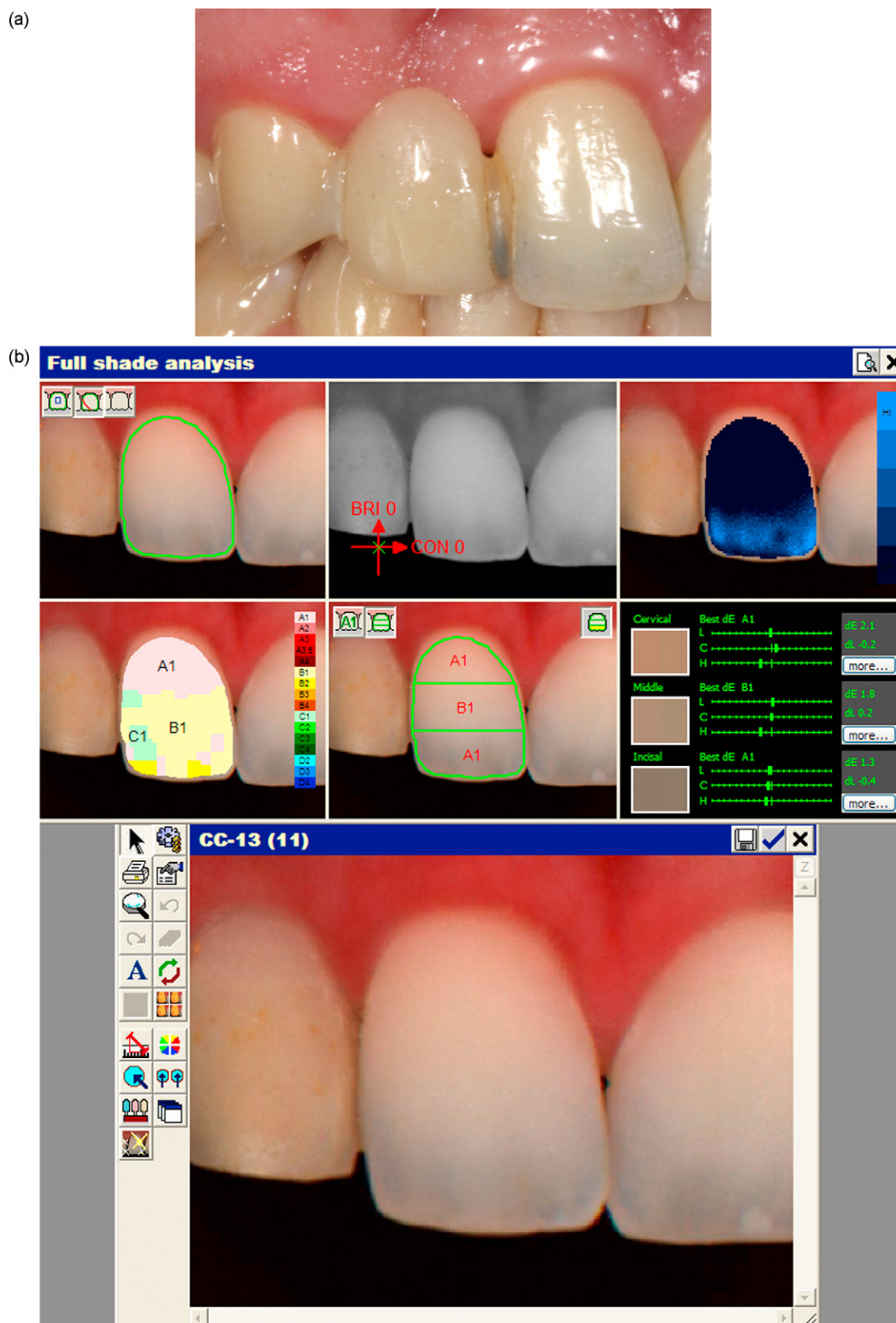


Fig. 5 – Clinical application SpectroShade Micro spectrophotometer. (a) Tooth #7 of a congenitally missing lateral incisor to be replaced with an implant [3i, Palm Beach, FL] and metal ceramic full coverage restoration. (b) The SpectroShade Micro system creates a color map which can be converted to several shade guide systems, this being the Classic Vita Shade Guide. It provides either an overall shade or the shade can be broken down into three distinct areas, cervical, middle and incisal, and provides detailed shade information in each of these areas and will provide a mathematical analysis resulting in a ΔE^* value. (c) Virtual shade verification can be formed with this system so that shades can be assured prior to time consuming patient visits. (d) Final restoration of tooth #7 with an implant and crown with an excellent aesthetic and functional outcome.

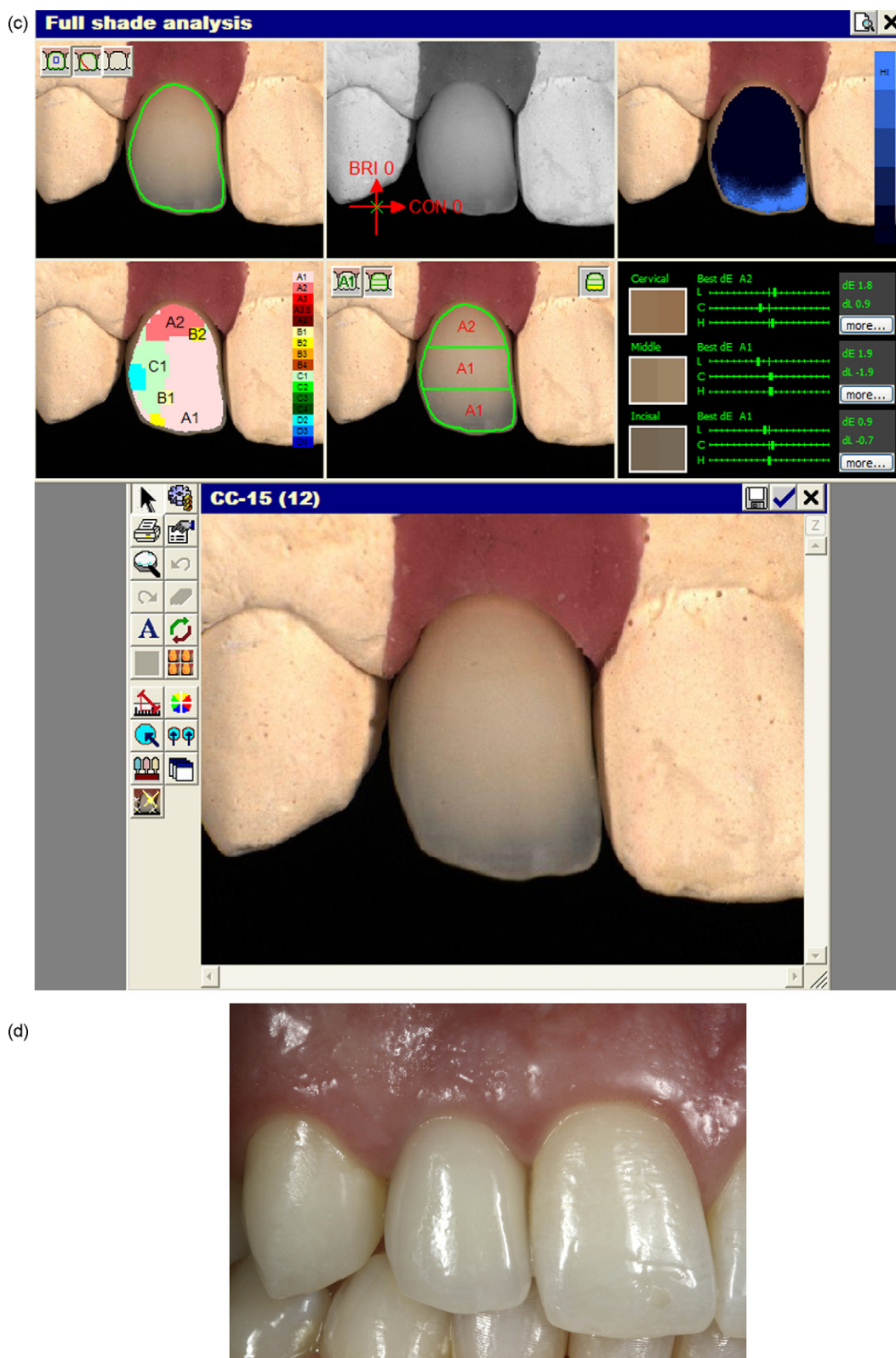


Fig. 5. (Continued).

strip showed the most intense staining ($p < 0.05$) and authors concluded that removing the Mylar layer by polishing is essential to achieving a stain resistant, more color stable composite surface.⁸⁶

Easyshade was also used in studying the effect of repeated firings (3, 5, 7, or 9 firings) on the color of an all-ceramic system with two different veneering porcelain shades (A1 and A3): The $L^*a^*b^*$ values of the ceramic system were affected by the



Fig. 6 – Technology-based systems provide shade tab information and then reference communication images are required by laboratory technicians to visualize the shade information. Gingival, body and incisal photographs should be submitted to the lab as a minimum requirement for shade reference.

number of firings (3, 5, 7, or 9) ($p < 0.001$) and the veneering porcelain shade ($p < 0.001$). Although the color of the specimens was influenced by repeated firings, recorded changes in color were clinically acceptable.⁸⁷ In another study by the same group, the effect of ceramic thickness and number of firings on the color of two all-ceramic systems was reported. The mean ΔE^* value increased as the thicknesses increased for both types of all-ceramic specimens tested. However, the difference between materials was significant.⁸⁸

Color stability of 3 veneering ceramics for zirconia frameworks was evaluated using SpectroShade. All materials exhibited significant color deviation from the reference teeth, with ΔE^* ranging from 5.6 to 6.8, but no significant differences were found between crowns and teeth for the 3 ceramics. The authors concluded that all 3 ceramics met the esthetic demands to a limited extent.⁸⁹ In an evaluation of a standard shade guide for color change after disinfection using Easyshade, a statistically significant increase in lightness and chroma were observed after 2 and 3 years of simulated treatments. However, these changes were not perceptible to the clinician.⁹⁰

Color stability of esthetic brackets made of different materials was evaluated using the Easyshade. The brackets were immersed for 10 days at 37 °C in various solutions, or exposed to accelerated photo-aging (150 kJ/m², 340 nm). It was found that the consumption of certain foods, such as red wine, tea, coffee and curry, greatly influenced the color changes of tooth-collared brackets.⁹¹

5.6. Tooth whitening

Color measurement devices have been used for bleaching studies to document shade changes.^{92–94} As indicated earlier,

one of the problems with shade matching especially for bleaching studies is positioning of the shade taking device. A flat surface is required to enable accurate placement during the shade measurement procedure. In addition, measurement near the incisal edge introduces error due to the translucent enamel allowing more light to be transmitted and not reflected to the shade taking device. Nonetheless, some clinicians feel a spectrophotometer can provide better comparison of shade change compared to a shade guide as a shade guide is non-linear. However a new Vita Bleachguide 3D-Master provides a more uniform color distribution in a linear fashion.⁹⁵ One study evaluated bleaching efficacy with and without supplementary light using Vitapan Classical and Bleachedguide 3D-Master in visual evaluation, and Easyshade spectrophotometer for instrumental evaluation.⁹⁶ A statistically significant difference between with- and without light treatment was registered using Bleachedguide and Easyshade, and greater color differences were recorded for baseline versus with light whitening. However, the ΔE^* values recorded in controlled conditions and by trained observers might not be perceivable in typical dental office conditions and by untrained observers. Clinical evaluation of different light-activated in-office bleaching systems revealed similar bleaching efficacy of four methods used: bleaching without light activation, diode laser activation, plasma arc lamp and a light emitting diode, with ΔE^* ranging from 5.3 to 5.7 (Easyshade).⁹⁷ Given the findings and less tooth and gingival sensitivity with diode laser, the authors suggested that this method might be the preferred in-office bleaching.

When two over the counter products, a 6% hydrogen peroxide (HP) bleaching gel delivered on polyethylene film and an 18% carbamide peroxide (CP) brush-applied liquid gel, were compared visually (Classical) and instrumentally (ShadeVision), both treatments caused significant tooth whitening. However, the HP-based product exhibited significantly greater efficacy.⁹⁸ Evaluation of the effect of laser tooth whitening revealed that teeth belonging to Classical group A showed greater shade improvement than teeth belonging to groups C and D. Whilst the whitening response was better in younger individuals, this response was not affected by gender. It should be noted that measurements were performed immediately after removal of the whitening gel, using ShadeEye NCC Dental Chroma Meter.⁹⁹ Another paper reported that Nd:YAG laser associated with hydrogen peroxide bleached the enamel, similarly to whitening efficacy obtained with the traditional method performed with halogen light.¹⁰⁰

Digital imaging has also been used for tooth whitening monitoring. In one study, digital imaging implied that 35% carbamide peroxide was more effective for darker teeth than 10% solution of the same agent.¹⁰¹ Several studies stated that their digital imaging system is reproducible and reliable in evaluating changes in whiteness of teeth¹⁰² and that clinical measurement of tooth color was highly reproducible with very high intra-class correlations for the image pairs.⁵³ Using the imaging system tested in reference 53, it was found that: (a) twice-daily use of 6% hydrogen peroxide whitening strips resulted in teeth becoming lighter and less yellow compared to baseline during initial 2-week use¹⁰³; (b) short-term color rebound after treatment may impact the utility of in-office tooth whitening with peroxide and light as a stand-alone

esthetic procedure¹⁰⁴; and (c) two professional at-home tooth whitening systems in a teenage population resulted in significant reduction in yellowness and increase in lightness after two weeks of treatment on each arch. No significant difference between groups was recorded.¹⁰⁵

5.7. Color interactions

Dental and professional color measurement devices have been used for quantifying of translucency-dependent color interactions. It was reported that different metal substructures and different porcelains significantly affected the final color of the restoration.¹⁰⁶ Changing the enamel porcelain thickness was found to have a greater effect on elevated chromatic shades compared to those of a lower chroma,¹⁰⁷ whereas semitranslucent all-ceramic materials achieved more accurate shade matches at reduced thickness of translucent porcelain than metal ceramic or semi-opaque all-ceramic crowns.¹⁰⁸ It was found that composite cements created perceptible color differences with particular combinations of die material, cement and ceramic crown,¹⁰⁹ and that final color of thinner specimens was significantly affected by the shade change and thickness of luting agent.¹¹⁰ Different backgrounds also influenced color of glass-infiltrated ceramic veneers,¹¹¹ whilst In-Ceram Alumina ceramic veneers showed the greatest improvement in the color performance of discolored teeth.¹¹²

In addition to layering, physical translucency can contribute to overall color shifting (color adjustment potential, blending) of restorative materials. Blending effect in the narrow sense is optical illusion, not measurable by any device, while more widely understood it also encompass the objective and measurable shifting caused by physical translucency. Blending effect was found to be material and shade dependent, and it increased with the decrease of restoration size.¹¹³ It increased with the decrease of initial color differences and the increase of translucency.¹¹⁴ Blending effect and double-layer effect were found to be directly proportional and highly correlated.¹¹⁵

6. Conclusion

The blending of science and art is something the dental industry is primed for. Patients are demanding contemporary esthetic dentistry, which has prompted the industry to continuously raise the bar with regard to esthetic detail. Many factors can influence the perception of color; by taking advantage of today's shade-matching technology, the subjectivity of color assessment can be minimized and accurate diagnosis of a restoration's shade is more easily communicated.

Complete tooth surface and limited area tooth surface measurement devices exist and either measure the complete tooth surface providing a "color map" or a smaller diameter [3–5 mm] on the tooth surface, respectively. Complete tooth measurement devices average the color in a larger area versus limited area measurement devices which measure a smaller area. These instruments are all useful supplementary tools in color analysis for direct or indirect restorations, communication for indirect restorations, reproduction and verification

of shade. Color communication is best performed using reference photography with reference shade tabs from current shade guide systems obtained using digital camera.

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. This includes evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and research on color compatibility, color stability including tooth whitening and color interactions of human teeth and dental materials.

Chances are that new affordable high-quality color matching instruments and technology will contribute to successful work with color and esthetic dentistry in general, particularly if complemented with better color-related education and training of dental professionals and advancement of dental materials. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

Conflict of Interest

Dr. Paravina is a paid consultant for Vita Zahnfabrik.

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Attachment A-2

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Review

Dental color matching instruments and systems. Review of clinical and research aspects

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ABSTRACT

Objectives: To review current status of hand held systems for tooth color matching in vivo and corresponding research.

Sources: “Medline” database from 1981 to 2010 were searched electronically with key words tooth, teeth, color and dentistry.

Conclusion: Spectrophotometers, colorimeters and imaging systems are useful and relevant tools for tooth color measurement and analysis, and for quality control of color reproduction. Different measurement devices either measure the complete tooth surface providing a “color map” or an “average” color of the limited area [3–5 mm] on the tooth surface. These instruments are useful tools in color analysis for direct or indirect restorations, communication for indirect restorations, reproduction and verification of shade. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

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1. Introduction

The interest in color research in dentistry has increased significantly over the past several decades. When keywords color and dentistry were used for Medline search, only 107 papers were found by 1970. In subsequent decades, the number of references increased as follows: 409 (1980), 1134 (1990), 2259 (2000) and 4062 (April 2010). Advancements in technology, computers, the Internet, and communication systems have greatly affected and shaped modern society. Commensurate with these strides are the advancements in contemporary dentistry. During the past half decade, the

dental profession has experienced the growth of a new generation of technologies devoted to the analysis, communication and verification of shade. Shade determination for direct and indirect restorations has always been a challenge for the esthetic dentist. Clark in 1931 described this in the Color Problems in Dentistry.¹ As opposed to subjective visual shade selection with not always quite controlled conditions and methods, and shade guides that exhibited significant shortcomings, several authors tried to objectively quantify tooth color in the past. This was done through identifying color problems in dentistry²; the importance of the quantity and quality of light required to properly analyse shade³

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through studying correlation between extracted teeth and shade guides⁴ or the development of the early shade measuring instruments and shade guides.⁵

The late 1990s marked the birth of a new industry in dentistry, commercially available instrument-based color measurement systems, with the development of the ShadeScan system (Cortex Machina, Montreal, Canada).⁶ This was the first effort toward a shade analysis system for complete tooth surface measurement. Prior literature published by several authors described limited area measurement instruments, with an optical diameter of 3–5 mm, in the analysis of shade.^{7–9} Another study evaluated clinical application of the ShadeScan prototype which employed digital camera technology, in a case report comparing visual vs. instrument-based shade information in the restoration of a single maxillary central incisor.¹⁰

Today's shade-matching technologies have been developed in an effort to increase the success of color matching, communication, reproduction and verification in clinical dentistry, and, ultimately, to increase the efficiency of esthetic restorative work within any practice. The aim of this paper is to provide a comprehensive review of the current state of shade-matching technologies and instrumentation, and their clinical and research application.

2. Rationale

Dental shade-matching instruments have been brought to market to reduce or overcome imperfections and inconsistencies of traditional shade matching. The most commonly used shade-matching method is the visual method, whilst Vitapan Classical (Vita Zahnfabrik, Bad Säckingen, Germany) and its derivations are probably the most commonly used shade guides. The colored tabs of distinctive shades organize the empiric-based Vita chart.^{11–14} In addition, unequivocal findings were reported on color consistency amongst shade guides from the same manufacturer.^{15,16} Introduction of evidence-based Vitapan 3D-Master shade guides, Toothguide, Bleachedguide and particularly Linearguide by the same manufacturer correspond to color of human teeth and therefore increase chances for successful shade matching.^{17,18}

Historically, assessing shade visually has been characterized by several innate difficulties: metamerism, suboptimal color matching conditions, tools and method as well as the receiver's age fatigue, mood and drugs/medications.¹⁹ Despite these difficulties, the human eye can discern very small

differences in color. However, the ability to communicate the degree and nature of these differences is lacking.

The final color of an all-ceramic restoration is a merging of the underlying tooth structure or core and the ceramic material. The color of the final restoration cannot match the shade selected from a shade guide unless this modification is taken into account. Therefore, a stump or base tooth preparation shade needs to be obtained and transmitted to the technician.²⁰

3. Overview

Instruments for clinical shade-matching encompass spectrophotometers, colorimeters and imaging systems. As with any device, benefits and limitations exist, and the clinician must consider how the technology relates to expectations and needs. Intra-oral color measuring devices have been designed to primarily fit the needs of clinical dentistry, such as information on the corresponding shade tabs, tooth translucency, or information associated with color communication, reproduction and verification. This, together with price limitation dictated by the dental market, resulted in having scientific aspects, such as providing reflectance values or color formulation, less emphasized. Another significant difference compared to other, non-dental applications, are optical properties of human teeth—they are small, curved, multi-layered, translucent and exhibit color transitions in all directions (gingival to incisal, mesial to distal and labial to lingual). This is why the accurate repositioning (measurement of the same area) is frequently of critical importance for either clinical and research use of dental color matching devices. The list of instruments and software for in vivo color matching and their properties is given in Table 1.²¹

In addition to the instruments listed in Table 1, there are numerous dental color matching products that are presently withdrawn from the market, of limited availability, or undergoing major redesigning. The list includes Chromascan (Sterngold, Stamford, CT, USA), Dental Color Analyzer (Wolf Industries, Vancouver, Canada), Identacolor II (Identa, Holbaek, Denmark), Digital Shade Guide DSG4 (A. Reith, Schorn-dorf, Germany), Ikam (Metalor Technologies, Attleboro, MA, USA), ShadeEye NCC Chroma Meter (Shofu Dental, Menlo Park, CA, USA), Beyond Insight Shade Taking Device (Beyond Dental & Health, Beijing, China), Shadescan (Cynovad, Montreal, Canada) and Vita Easyshade (Vita Zahnfabrik, Bad Säckingen, Germany).

Table 1 – Instruments and software for color matching in dentistry: types, measurement area and relative cost (\$1000–\$7500).²¹

Product	Manufacturer	Device type	Measurement area	Relative cost
ClearMatch	Clarity Dental, Salt Lake City, UT	Software, digital image analysis	Complete tooth image	Low
CrystalEye	Olympus America, Center Valley, PA	Imaging Spectrophotometer	Complete tooth image	High
Easyshade Compact	Vident, Brea, CA	Spectrophotometer	5-mm probe diameter	Low
Shade-X	X-Rite, Grandville, MI	Spectrophotometer	3-mm probe diameter	Low
ShadeVision	X-Rite, Grandville, MI	Imaging colorimeter	Complete tooth image	Moderate
SpectroShade Micro	MHT, Niederhasli, Switzerland	Imaging Spectrophotometer	Complete tooth image	Moderate

4. Characteristics and clinical application

4.1. Spectrophotometers

Spectrophotometers are amongst the most accurate, useful and flexible instruments for overall color matching and color matching in dentistry.²² They measure the amount of light energy reflected from an object at 1–25 nm intervals along the visible spectrum.^{23,24} A spectrophotometer contains a source of optical radiation, a means of dispersing light, an optical system for measuring, a detector and a means of converting light obtained to a signal that can be analysed. The data obtained from spectrophotometers must be manipulated and translated into a form useful for dental professionals. The measurements obtained by the instruments are frequently keyed to dental shade guides and converted to shade tab equivalent.²⁵ Compared with observations by the human eye, or conventional techniques, it was found that spectrophotometers offered a 33% increase in accuracy and a more objective match in 93.3% of cases.²⁶

Crystaleye (Olympus, Tokyo, Japan) combines the benefits of a traditional spectrophotometer with digital photography. Through the development of optical and image processing technology, this product allows the practitioner to match tooth shade and color more accurately and simply compared with the traditional spectrophotometer.²⁷

The significant benefit of this system is that ‘virtual shade tabs’ in the computers database can be cross-referenced and superimposed visually onto the natural tooth image to be matched giving the technician the ability to visualize the correct shade tabs. The digital image produced by the Crystaleye uses a 7-band LED light source, which results in a more precise depiction of color than the conventional systems used with digital cameras. Moreover, the image produced by the Crystaleye is taken from inside the oral cavity and consequently is devoid of the external light that can cause discrepancies.

Vita Easyshade Compact (Vita Zahnfabrik, Bad Säckingen, Germany) is cordless, small, portable, cost efficient, battery operated, contact-type spectrophotometer that provides enough shade information to help aid in the color analysis process. Different measurement modes are possible with Easyshade Compact: tooth single mode, tooth area mode (cervical, middle and incisal shades), restoration color verification (includes lightness, chroma and hue comparison) and shade tab mode (practice/training mode).²⁸

Shade-X (X-Rite, Grandville, MI) is also compact and cordless “spot” measurement” spectrophotometer with 3-mm probe diameter, and keyed to the majority of popular shade guides. Shade-X have two databases to match the color of the dentin (more opaque) and the incisal tooth regions (more translucent).²⁹

SpectroShade Micro (MHT Optic Research, Niederhasli, Switzerland) is an imaging spectrophotometer. It uses a digital camera/LED spectrophotometer combination. It has an internal computer with the analytical software. The tooth positioning guidance system, shown on the LCD touch screen, is used during color measurement. Images and spectral data can be saved on the internal memory and transferred to a computer.³⁰

4.2. Colorimeters

Colorimeters measure tristimulus values and filter light in red, green and blue areas of the visible spectrum. Colorimeters are not registering spectral reflectance and can be less accurate than spectrophotometers (aging of the filters can additionally affect accuracy).³¹ ShadeVision (X-Rite, Grandville, MI) is an imaging colorimeter. Complete tooth image is provided through the use of three separate databases: for gingival, middle and incisal third. Virtual try-in feature enables virtual testing of color reproduction during fabrication.³²

4.3. Digital cameras and imaging systems

Digital Cameras. Most consumer video or digital still cameras acquire red, green and blue image information that is utilized to create a color image. The RGB color model is an additive model in which red, green and blue light are added together in various ways to reproduce a broad array of colors. Digital cameras represent the most basic approach to electronic shade taking, still requiring a certain degree of subjective shade selection with the human eye.³³ Various approaches have been used to translate this data into useful dental color information.

ClearMatch (Smart Technology, Hood River, OR) is a software system that uses high-resolution digital images and compares shades over the entire tooth with known reference shades.³⁰ Similar to the software associated with color measuring devices, ClearMatch contains the color database of industry-standard shade guides.³⁴

4.4. Interpretation and application of shade analysis data

Complete tooth surface measurement [CTSM] devices give a color map of the gingival, body and incisal shades for the fabrication of direct or indirect restorations. These systems give a virtual shade overlay of the proposed tab onto the digital image on the computer screen of the tooth measured for visual reference and assessment by the clinician and/or technician. CTSM spectrophotometers, such as Crystaleye and SpectroShade, provide shade tab designation and the respective ΔE^* values compared to shade tab values in the memory. However, these mappings are two dimensional and they do not necessarily take into account the shape, texture, thickness of the restoration, type of abutment and different core material (metal or ceramic).³⁵ In addition, they ‘average out’ color data over the complete tooth surface or larger defined areas which can lead to inaccurate shade information.

Limited area measurement devices provide 3–5 mm diameter areas of the tooth being measured. Therefore several areas of the tooth should be considered to obtain a representative evaluation of tooth shade. At a minimum, a limited area measurement of the gingival, body and incisal areas of the tooth [total of 3 measurements] should be assessed and recorded for the technician if an indirect restoration is prescribed. It was found that decreasing the window size when examining extracted teeth with a spectrophotometer and spectroradiometer resulted in lower CIE $L^*a^*b^*$ values.³⁶ Small-window tooth color measurement may cause edge loss of the light due to a tooth’s translucency.³⁷

Once the technology-based information is analysed, the information must be communicated to the technician for indirect restorations.³⁸ The aforementioned instruments and technologies are predominantly intended for shade analysis, however, this information alone may be insufficient for the technician to adequately interpret the shade information provided. Subsequent reference photography is highly recommended for communication on tooth color. Digital photographs are an important adjunct to the laboratory technician and together with the shade or “color map” should be sufficient communication material to construct an acceptable restoration.

Clinicians and technicians are frequently located in different areas. A digital camera permits the transfer of images from the clinician to the technician. The best way to reference shade information is by using shade tabs to communicate shade.³⁹ A systematic protocol to referencing shade information as well as changes in shade between tabs is required. Shades identified in the digital map are arranged by gingival (G), middle (M) and incisal third (I). The shade tabs should be selected and photographs should be taken with each tab in its proper orientation in reference to the tooth.

Camera and light settings and image format must be kept constant at all times for consistent shade color communication. In addition to the three basic shade tabs representing the respective G, M and I shades, two additional reference shade tab photographs should be included to graduate and calibrate shifts in hue, chroma and value between physical tabs visually in the laboratory, in the photographs and between the photos. One selected tab should be lighter in shade and one darker in shade in respect to the selected basic shades. The combination of accurate digital shade analysis information coupled with standardized reference shade communication photography can ensure a predictable esthetic restorative outcome of the final direct or indirect restoration.

Indirect restorations can and should be verified visually and with the instrument system in the laboratory prior to being returned to the clinician. This verification process can streamline wasteful chair side time attributed to remakes due to incorrect shade.^{40,41} Clinical excellence backed with sound color science and its appropriate interpretation can probably make the critical difference between good to excellent.⁴² Examples of color matching, interpretation and application of shade analysis data are given in Figs. 1–6.

5. Research

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. The most frequent research topics associated with these instruments and systems are associated with evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and evaluation on color compatibility, stability and interactions of human hard and soft oral tissues, head and neck tissues and dental materials. Although non-dental, professional bench-top color measurement instruments were used in many research projects in dentistry, this paper will focus mainly on these conducted using hand held devices designed for dental application.

5.1. Measurement uncertainties

In color science, evaluation of measurement uncertainties of shade-matching instruments is performed through precision and accuracy testing. The uncertainties associated with precision are most frequently associated with random errors, whilst the uncertainties associated with accuracy usually originate from systematic errors. Precision is tested by evaluation of repeatability (same method, operator or instrument) and reproducibility (different method, operator and/or instrument). Based on time interval, we are talking about short term (measurements in succession), medium term (hours) and long term measurements (weeks or longer). Based on the specimen manipulation, measurement can be performed with- and without replacement.⁴³ Evaluation of measurement uncertainties encompasses the use of referent instrument, preferably professional, non-dental, color measuring instrument.³⁷

In a study that compared five dental color measuring devices—ShadeScan, Easyshade, Ikam, IdentaColor II and ShadeEye, five group A Classical tabs were in vitro measured five times by two operators, whilst 25 upper right central incisors were measured in vivo by one operator. The best precision in vivo was recorded for Easyshade and Ikam, whilst performance of the other instruments was better in vitro than in vivo.¹² In an another study, SpectroShade, ShadeVision, VITA Easyshade and ShadeScan were evaluated.³¹ High reliability (reproducibility?) and variability in accuracy was reported. One in vitro study found that repeatability and accuracy of a dental color measuring instrument (ShadeScan) was influenced by shade guide systems used for testing.⁴⁴ When the precision of measurement of different tooth areas was evaluated, the middle third of each labial tooth surface exhibited the most consistent results.⁴⁵

Dental color matching instruments also provide the information on best matching tabs from different shade guides.^{25,46,47} This application-specific color information is also of importance and therefore requires proper attention of dental researches. When VITA EasyShade and ShadeEye NCC were tested on extracted human teeth, there were discrepancies in shade guide designations provided by the instruments. Higher inter-device agreement was recorded for Vitapan Classical than for Vitapan 3D-Master.²⁵

Digital imaging systems are becoming increasingly popular in determining the color of teeth. Precision and accuracy of these systems are influenced by the quality of camera and image processing method. Several studies reported that digital cameras, may be reliable instruments for determining the color of teeth and gingiva when combined with the appropriate calibration protocols.^{48–54}

Clinical imaging and conventional image processing methods such as Adobe Photoshop and Corel Photo-Paint are suitable for many purposes in dentistry: lab communication, documentation, patient education and others. However, scientific imaging,⁵⁵ appropriate methods of data processing and color science terminology is preferred in dental research. This, together with lack of the referent instrument (the instrument that has already been validated, not necessary by the same authors), diminished the validity of some studies on precision and accuracy of dental color matching instruments.

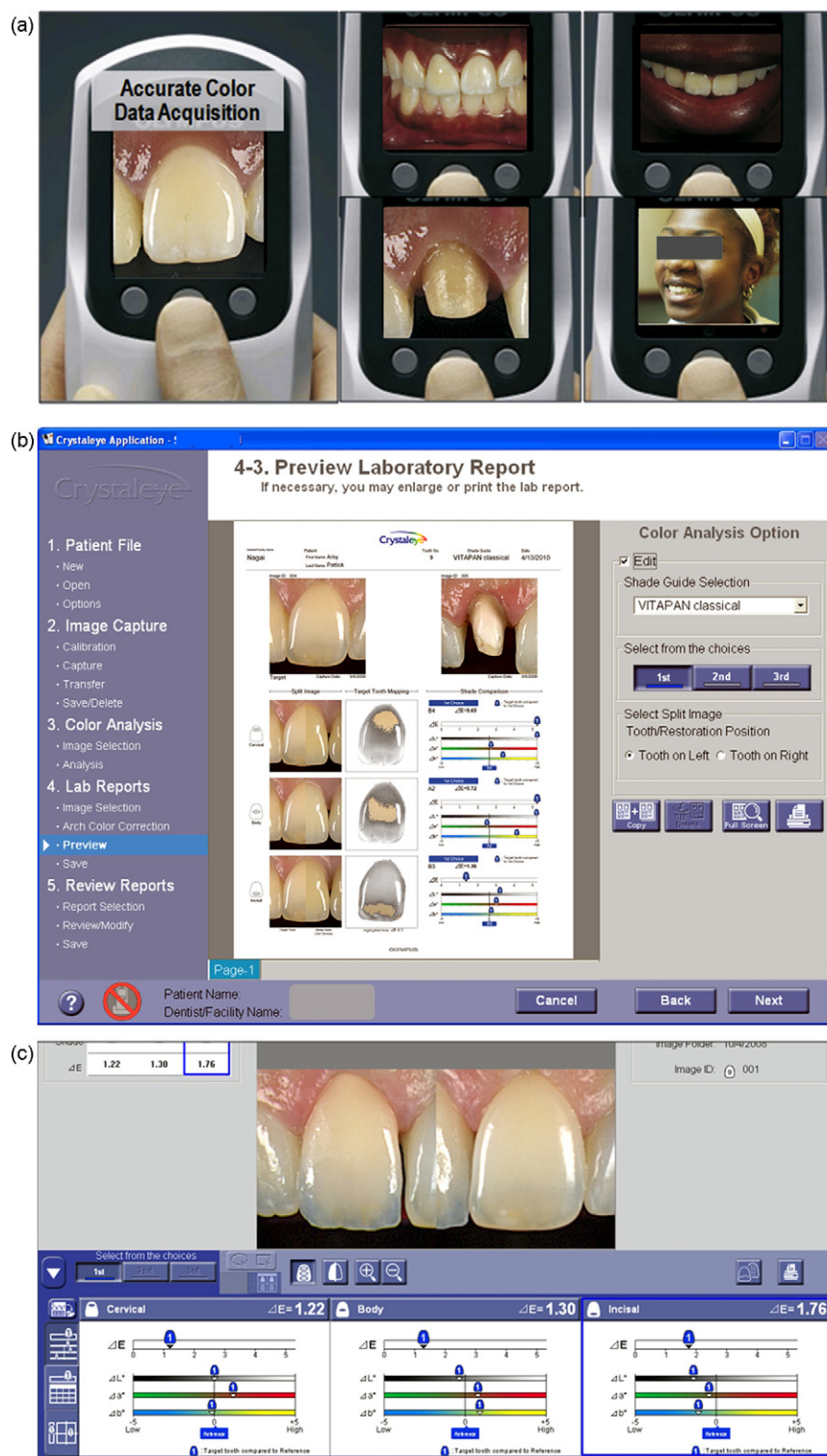


Fig. 1 – Clinical application of CrystalEye spectrophotometer (Courtesy Dr. Shigemi Nagai). (a) CrystalEye captures the spectral image of the tooth, abutment, arch and full face image. (b) Laboratory report can be sent to the lab as a quick color note. (c) Color analysis of the ceramic crown (after 1st bake try-in) placed on the abutment. Excellent color match was confirmed in the cervical and body areas. Minor modification may be required in the incisal area to increase the value and yellowness. (d) Color difference ΔE s obtained in all 3 areas are considered to be excellent color match. L^* value map indicates indistinguishable value distribution on #8 and #9.

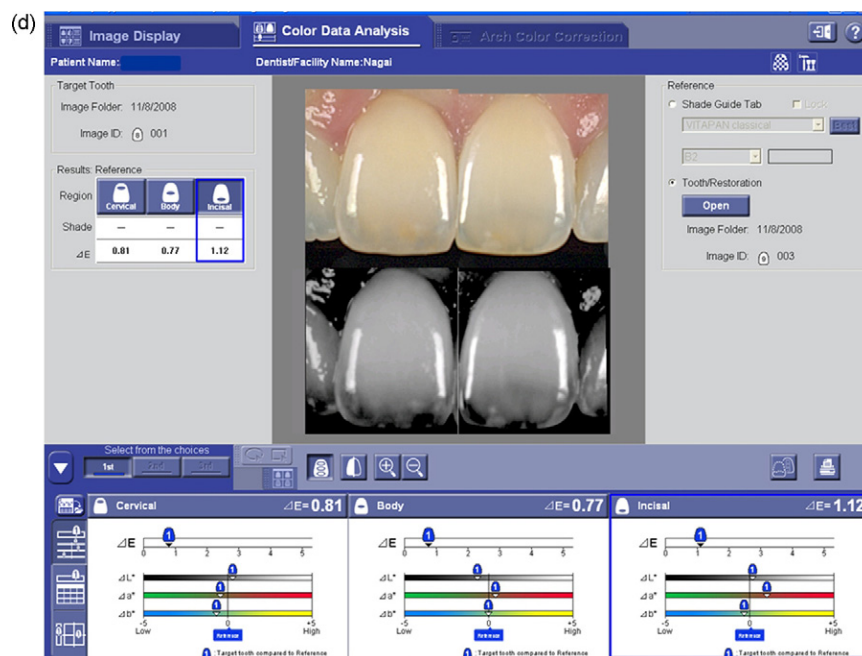


Fig. 1. (Continued).

5.2. Comparison between visual and instrumental findings

When the first dental color measuring instruments appeared, they exhibited slightly better accuracy compared to visual findings that were described as inconsistent.⁵⁶ Since that time, the modernization of both visual and instrumental means for color matching in dentistry occurred.^{17,57} More recently, better results were reported with dental spectrophotometer than using the visual method in approximately 47% of the cases,⁵⁸ which is in accordance with independent studies that documented the supremacy of spectrophotometric color matching compared to visual shade assessment.^{27,59} Another paper reported that the performance of Easyshade was comparable or better than that of dentists, whilst the agreement between visual and instrumental findings was qualified as good to very good.⁶⁰ In another paper, it was found that the agreement amongst the observer groups was significantly better than that of each device and that color matching instruments did not reflect human perception.⁶¹

It was found that consensus amongst observers led to better shade-matching results with some shade guides, compared to results of individual observers,⁶² and that intraexaminer shade-matching agreement was mainly acceptable.⁶³ Significantly higher visual-instrumental agreement was recorded for experienced dentists (compared to dental students and non-dental observers), regardless of shade guides and lighting conditions.⁶⁴

The comparison between visual and instrumental findings is a very attractive topic as it reveals pros and cons of both methods. Visual color matching is subjective and influenced by variety of factors. However, this method is not inferior and should not be underrated. Actually, the all “objective” color measuring instruments have been developed based on the

visual response of the “standard observer” and they are good only if they match that response. In addition, the numerically smallest ΔE^* value does not necessarily correspond to the best match because of the uneven eye sensitivity to hue, value and chroma differences. Therefore, the answer whether to use visual or instrumental method for color matching in dentistry is: whenever if possible, use both, as they complement each other and can lead towards predictable esthetic outcome.^{39–41}

5.3. Evaluation of visual color thresholds

Perceptibility and acceptability visual thresholds can be quantified only by combining visual and instrumental color measurement methods. Although majority of studies used professional (non-dental) color measuring devices in threshold evaluation, this topic is of exceptional importance in interpretation of color differences in clinical dentistry and dental research.

When the color difference between compared objects can be seen by 50% of observers (the other 50% will notice no difference), we are talking about the 50:50% perceptibility threshold.⁶⁵ When the color difference is considered acceptable 50% of observers (the other 50% would consider it unacceptable), this corresponds to 50:50% acceptability threshold. A color match in dentistry is a color difference at or below the former threshold, an acceptable color match is a color difference at or below the later one.⁶⁵

In dental literature, it is frequently interpreted that a ΔE^* of 1 is the 50:50 perceptibility threshold under controlled conditions (50% of observers will notice the color difference and 50% will see no difference between compared objects),⁶⁶ whereas a ΔE^* of 2.7⁶⁷ and 3.3⁶⁸ were found to be 50:50 acceptability thresholds (50% of observers will accept the restoration and 50% will replace it because of color mismatch).



Fig. 2 – Clinical application of EasyShade Compact spectrophotometer. (a) Instrument calibration. (b) Color measurement. (c) Color difference metric values as compared to the corresponding Vitapan Classical shade. (d) Color coordinate values and the corresponding Vitapan 3D-Master shade.

Several other studies, more or less controlled, reported the variability of findings on visual color thresholds.^{57,69–71} This, in addition to the introduction of new color difference formulae (CIEDE2000), suggests systematic approach and standardization of methods.

5.4. Color compatibility

Color compatibility studies encompass comparisons amongst teeth, shade guides and dental materials. Evaluation of color of natural teeth is important for clinical dentistry since knowledge on color ranges and color distribution of natural teeth can provide guidelines for designing of dental materials that will enable better and easier match to natural teeth.^{13,72} Databases encompassing spectral properties of teeth, regardless whether created using dental or non-dental color measuring devices, are of particular validity.⁷³ Two independent studies, both performed using Vita Easyshade, reported almost the same color coordinate ranges of natural teeth: $L^* = 55.5\text{--}89.6$ ⁷⁴ and $L^* = 58.7\text{--}88.7$ ⁷⁵; $a^* = 4.2\text{--}7.3$ ⁷⁴ and $a^* = 3.6\text{--}7.0$ ⁷⁵, and $b^* = 3.6\text{--}38.9$ ⁷⁴ and $b^* = 3.7\text{--}37.3$.⁷⁵ Current

shade guides exhibit moderate to pronounced discrepancy with results recorded for natural teeth. This discrepancy has been quantified by calculation of coverage error, the mean value of the minimal color differences amongst



Fig. 3 – Clinical application of Shade-X spectrophotometer.

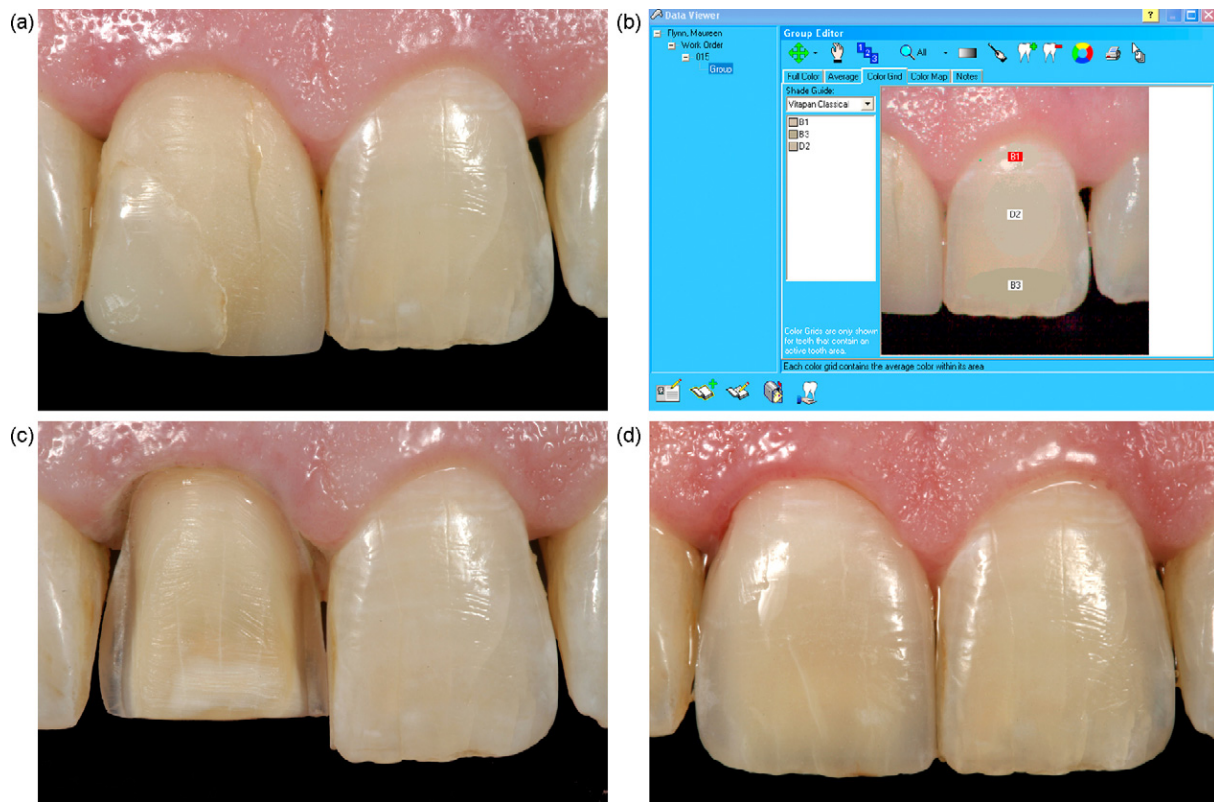


Fig. 4 – Clinical application of ShadeVision colorimeter. (a) The fractured veneer restoration on tooth #8 is to be replaced with a new veneer restoration. (b) The ShadeVision color mapping for tooth #9 to be matched with gingival, body and incisal shade reference tabs. (c) Veneer preparation tooth #8. It is important that an even thickness of tooth reduced is performed to insure color control of ceramic layering for predictable shade matching of the restoration. (d) Insertion of veneer restoration tooth #8 [Venus porcelain, Heraeus, Hanau, Germany] which matches the contralateral tooth satisfactorily and predictably without a remake.

each tab in the shade guide and the database of human teeth.^{17,73–76}

Although teeth exhibit color transitions in all directions, the correlation between colors of different regions on the labial tooth surface has been recorded. This study, performed using digital camera, suggested that color of a missing part of a tooth can be determined using the color of existing areas.⁷⁷ The same team reported color correlation between maxillary incisors and canines, which may influence color matching of missing teeth.⁷⁸

As far as the compatibility amongst materials is concerned, different comparisons have been performed. An Easyshade comparison between Vitapan Classical shade guide and four different veneering porcelain systems for metal ceramic restorations, revealed that differences were shade-dependent: A2 porcelain disks exhibited better match to corresponding VITA shade, followed by A3 and A3.5 disks.⁷⁹ The same instrument was used to test the ability of a ceramic system to correctly reproduce the shade selected using two shade guides. Toothguide 3D-Master outperformed VITA Classical.⁸⁰ When the quality of color match of different shade guides and corresponding porcelains was evaluated, the highest percentage of clinically acceptable matches was recorded for Toothguide 3-D Master/Omega 900 combination.⁸¹ A study, conducted using Easyshade,

reported that evaluated resin composites exhibited poor match compared to target Vitapan Classical tabs of the same shade designations.⁸² Similar conclusions were derived when various composites of corresponding shades were compared with a shade guide using a non-dental colorimeter,⁸³ and with each other using a bench-top spectrophotometer.⁸⁴

5.5. Color stability

Color stability of teeth and dental restoration is one of the prerequisites for long-lasting esthetics of dental restorations. Dental materials can exhibit color shifting during fabrication or at placement, and after placement. The later type of color shifting is associated with aging and staining.

When nanofill composite specimens were immersed into coffee, yerba mate, grape juice or water (control solution) for one week and tested using Easyshade, perceivable color change was observed only for the group immersed into the grape juice.⁸⁵ Another study used Easyshade to evaluate resin composites polished with two one-step polishing systems and exposed to coffee solution for seven days. Although all materials exhibited significant color changes, statistically significant polishing system-dependent differences were recorded ($p < 0.05$). Composite polymerized against Mylar

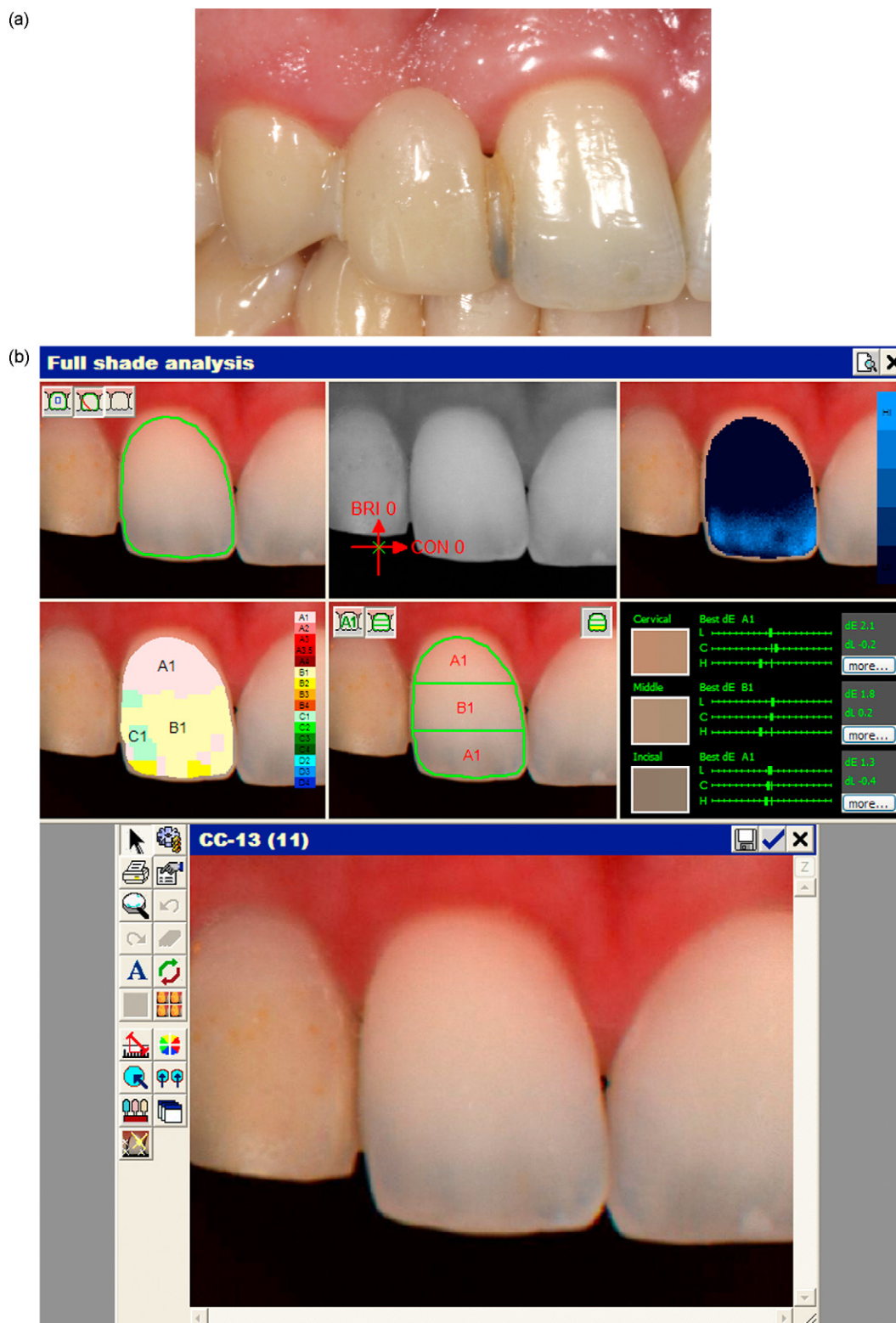


Fig. 5 – Clinical application SpectroShade Micro spectrophotometer. (a) Tooth #7 of a congenitally missing lateral incisor to be replaced with an implant [3i, Palm Beach, FL] and metal ceramic full coverage restoration. (b) The SpectroShade Micro system creates a color map which can be converted to several shade guide systems, this being the Classic Vita Shade Guide. It provides either an overall shade or the shade can be broken down into three distinct areas, cervical, middle and incisal, and provides detailed shade information in each of these areas and will provide a mathematical analysis resulting in a ΔE^* value. (c) Virtual shade verification can be formed with this system so that shades can be assured prior to time consuming patient visits. (d) Final restoration of tooth #7 with an implant and crown with an excellent aesthetic and functional outcome.

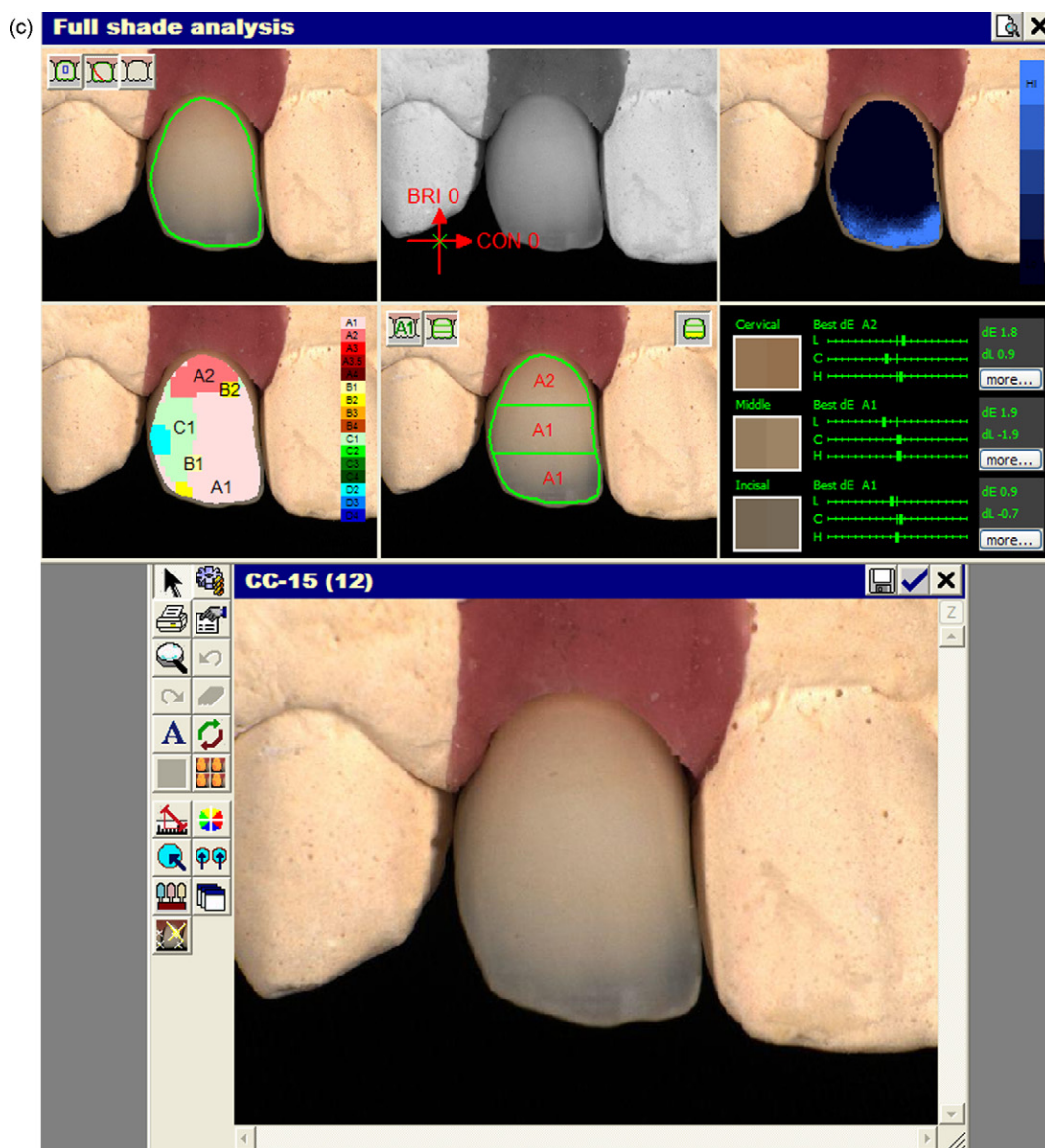


Fig. 5. (Continued).

strip showed the most intense staining ($p < 0.05$) and authors concluded that removing the Mylar layer by polishing is essential to achieving a stain resistant, more color stable composite surface.⁸⁶

Easyshade was also used in studying the effect of repeated firings (3, 5, 7, or 9 firings) on the color of an all-ceramic system with two different veneering porcelain shades (A1 and A3): The $L^*a^*b^*$ values of the ceramic system were affected by the



Fig. 6 – Technology-based systems provide shade tab information and then reference communication images are required by laboratory technicians to visualize the shade information. Gingival, body and incisal photographs should be submitted to the lab as a minimum requirement for shade reference.

number of firings (3, 5, 7, or 9) ($p < 0.001$) and the veneering porcelain shade ($p < 0.001$). Although the color of the specimens was influenced by repeated firings, recorded changes in color were clinically acceptable.⁸⁷ In another study by the same group, the effect of ceramic thickness and number of firings on the color of two all-ceramic systems was reported. The mean ΔE^* value increased as the thicknesses increased for both types of all-ceramic specimens tested. However, the difference between materials was significant.⁸⁸

Color stability of 3 veneering ceramics for zirconia frameworks was evaluated using SpectroShade. All materials exhibited significant color deviation from the reference teeth, with ΔE^* ranging from 5.6 to 6.8, but no significant differences were found between crowns and teeth for the 3 ceramics. The authors concluded that all 3 ceramics met the esthetic demands to a limited extent.⁸⁹ In an evaluation of a standard shade guide for color change after disinfection using Easyshade, a statistically significant increase in lightness and chroma were observed after 2 and 3 years of simulated treatments. However, these changes were not perceptible to the clinician.⁹⁰

Color stability of esthetic brackets made of different materials was evaluated using the Easyshade. The brackets were immersed for 10 days at 37 °C in various solutions, or exposed to accelerated photo-aging (150 kJ/m², 340 nm). It was found that the consumption of certain foods, such as red wine, tea, coffee and curry, greatly influenced the color changes of tooth-collared brackets.⁹¹

5.6. Tooth whitening

Color measurement devices have been used for bleaching studies to document shade changes.^{92–94} As indicated earlier,

one of the problems with shade matching especially for bleaching studies is positioning of the shade taking device. A flat surface is required to enable accurate placement during the shade measurement procedure. In addition, measurement near the incisal edge introduces error due to the translucent enamel allowing more light to be transmitted and not reflected to the shade taking device. Nonetheless, some clinicians feel a spectrophotometer can provide better comparison of shade change compared to a shade guide as a shade guide is non-linear. However a new Vita Bleachguide 3D-Master provides a more uniform color distribution in a linear fashion.⁹⁵ One study evaluated bleaching efficacy with and without supplementary light using Vitapan Classical and Bleachedguide 3D-Master in visual evaluation, and Easyshade spectrophotometer for instrumental evaluation.⁹⁶ A statistically significant difference between with- and without light treatment was registered using Bleachedguide and Easyshade, and greater color differences were recorded for baseline versus with light whitening. However, the ΔE^* values recorded in controlled conditions and by trained observers might not be perceivable in typical dental office conditions and by untrained observers. Clinical evaluation of different light-activated in-office bleaching systems revealed similar bleaching efficacy of four methods used: bleaching without light activation, diode laser activation, plasma arc lamp and a light emitting diode, with ΔE^* ranging from 5.3 to 5.7 (Easyshade).⁹⁷ Given the findings and less tooth and gingival sensitivity with diode laser, the authors suggested that this method might be the preferred in-office bleaching.

When two over the counter products, a 6% hydrogen peroxide (HP) bleaching gel delivered on polyethylene film and an 18% carbamide peroxide (CP) brush-applied liquid gel, were compared visually (Classical) and instrumentally (ShadeVision), both treatments caused significant tooth whitening. However, the HP-based product exhibited significantly greater efficacy.⁹⁸ Evaluation of the effect of laser tooth whitening revealed that teeth belonging to Classical group A showed greater shade improvement than teeth belonging to groups C and D. Whilst the whitening response was better in younger individuals, this response was not affected by gender. It should be noted that measurements were performed immediately after removal of the whitening gel, using ShadeEye NCC Dental Chroma Meter.⁹⁹ Another paper reported that Nd:YAG laser associated with hydrogen peroxide bleached the enamel, similarly to whitening efficacy obtained with the traditional method performed with halogen light.¹⁰⁰

Digital imaging has also been used for tooth whitening monitoring. In one study, digital imaging implied that 35% carbamide peroxide was more effective for darker teeth than 10% solution of the same agent.¹⁰¹ Several studies stated that their digital imaging system is reproducible and reliable in evaluating changes in whiteness of teeth¹⁰² and that clinical measurement of tooth color was highly reproducible with very high intra-class correlations for the image pairs.⁵³ Using the imaging system tested in reference 53, it was found that: (a) twice-daily use of 6% hydrogen peroxide whitening strips resulted in teeth becoming lighter and less yellow compared to baseline during initial 2-week use¹⁰³; (b) short-term color rebound after treatment may impact the utility of in-office tooth whitening with peroxide and light as a stand-alone

esthetic procedure¹⁰⁴; and (c) two professional at-home tooth whitening systems in a teenage population resulted in significant reduction in yellowness and increase in lightness after two weeks of treatment on each arch. No significant difference between groups was recorded.¹⁰⁵

5.7. Color interactions

Dental and professional color measurement devices have been used for quantifying of translucency-dependent color interactions. It was reported that different metal substructures and different porcelains significantly affected the final color of the restoration.¹⁰⁶ Changing the enamel porcelain thickness was found to have a greater effect on elevated chromatic shades compared to those of a lower chroma,¹⁰⁷ whereas semitranslucent all-ceramic materials achieved more accurate shade matches at reduced thickness of translucent porcelain than metal ceramic or semi-opaque all-ceramic crowns.¹⁰⁸ It was found that composite cements created perceptible color differences with particular combinations of die material, cement and ceramic crown,¹⁰⁹ and that final color of thinner specimens was significantly affected by the shade change and thickness of luting agent.¹¹⁰ Different backgrounds also influenced color of glass-infiltrated ceramic veneers,¹¹¹ whilst In-Ceram Alumina ceramic veneers showed the greatest improvement in the color performance of discolored teeth.¹¹²

In addition to layering, physical translucency can contribute to overall color shifting (color adjustment potential, blending) of restorative materials. Blending effect in the narrow sense is optical illusion, not measurable by any device, while more widely understood it also encompass the objective and measurable shifting caused by physical translucency. Blending effect was found to be material and shade dependent, and it increased with the decrease of restoration size.¹¹³ It increased with the decrease of initial color differences and the increase of translucency.¹¹⁴ Blending effect and double-layer effect were found to be directly proportional and highly correlated.¹¹⁵

6. Conclusion

The blending of science and art is something the dental industry is primed for. Patients are demanding contemporary esthetic dentistry, which has prompted the industry to continuously raise the bar with regard to esthetic detail. Many factors can influence the perception of color; by taking advantage of today's shade-matching technology, the subjectivity of color assessment can be minimized and accurate diagnosis of a restoration's shade is more easily communicated.

Complete tooth surface and limited area tooth surface measurement devices exist and either measure the complete tooth surface providing a "color map" or a smaller diameter [3–5 mm] on the tooth surface, respectively. Complete tooth measurement devices average the color in a larger area versus limited area measurement devices which measure a smaller area. These instruments are all useful supplementary tools in color analysis for direct or indirect restorations, communication for indirect restorations, reproduction and verification

of shade. Color communication is best performed using reference photography with reference shade tabs from current shade guide systems obtained using digital camera.

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. This includes evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and research on color compatibility, color stability including tooth whitening and color interactions of human teeth and dental materials.

Chances are that new affordable high-quality color matching instruments and technology will contribute to successful work with color and esthetic dentistry in general, particularly if complemented with better color-related education and training of dental professionals and advancement of dental materials. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

Conflict of Interest

Dr. Paravina is a paid consultant for Vita Zahnfabrik.

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Attachment A-3

Review

Discolouration potential of endodontic procedures and materials: a review

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Abstract

Ahmed HMA, Abbott PV. Discolouration potential of endodontic procedures and materials: a review. *International Endodontic Journal*, **45**, 883–897, 2012.

Advances in endodontic materials and techniques are at the forefront of endodontic research. Despite continuous improvements, tooth discolouration, especially in anterior teeth, is considered an undesirable consequence following endodontic treatment as it creates a range of aesthetic problems. This article aims to discuss the intrinsic and internalized tooth discolouration caused by endodontic procedures, and to address the

discolouration potential of materials used during root canal treatment, including root canal irrigants, intra-canal medicaments, endodontic and post-endodontic filling materials. In addition, the discolouration patterns caused by combined endodontic and non-endodontic aetiological factors are discussed. The recommended guidelines that should be followed by dental practitioners to prevent and manage tooth discolouration are also outlined.

Keywords: discolouration, endodontic materials, endodontic procedures, review.

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Introduction

The appearance of teeth is of particular cosmetic importance with increasing interest amongst the public and dental practitioners (Hattab *et al.* 1999, Sulieman 2005). Tooth discolouration creates a range of aesthetic problems, and considerable amounts of time and money are invested in attempts to improve the appearance of discoloured teeth. Discolouration is a more significant factor for many people in achieving an aesthetic smile than restoring their normal alignment within the arch (Sulieman 2008). Therefore, it is important for dental professionals to have a thorough knowledge and

understanding of the aetiology and clinical features of tooth discolouration to select the most appropriate treatment for each case (Watts & Addy 2001).

Tooth discolourations can be classified as intrinsic (pre- and post-eruptive staining), extrinsic or a combination of both (Hattab *et al.* 1999, Plotino *et al.* 2008). 'Internalized tooth discolouration' is another category that describes the changes in normal tooth colour because of cracks, dentinal caries and dental restorations (Watts & Addy 2001, Sulieman 2005, 2008) (Table 1). In some clinical situations, coronal tooth discolouration may be the result of intra- and/or post-endodontic procedural errors, mainly attributed to inadequate knowledge of the discolouration potential of intra- and post-endodontic materials, which may be associated with non-endodontic aetiological factors (Table 2). Hence, this review was undertaken to identify the endodontic procedures and materials that may discolour teeth and to discuss the clinical implications including the preventive measures and treatment options.

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Table 1 Summary of various aetiological factors causing tooth discolouration and the colours produced (Suliman 2005, 2008)

Type of discolouration	Colour produced
I) Extrinsic	
a) <i>Direct stains</i>	
Tea, coffee and other foods	Brown to black
Cigarettes/cigars	Yellow/brown to black
Plaque/poor oral hygiene	Yellow/brown
b) <i>Indirect stains</i>	
Polyvalent metal salts and cationic antiseptics (e.g. chlorhexidine)	Black and brown
II) Intrinsic	
a) <i>Metabolic causes</i>	
e.g. congenital erythropoietic porphyria	Purple/brown
b) <i>Inherited causes</i>	
e.g. amelo/dentinogenesis	Brown or black
c) <i>Iatrogenic causes</i>	
Tetracycline	Classically yellow, brown, blue, black or grey
Fluorosis	White, yellow, grey or black
d) <i>Traumatic causes</i>	
Enamel hypoplasia	Yellow brown or white
Pulp haemorrhage products	Grey Brown to black
Root resorption	Pink spot
e) <i>Idiopathic causes</i>	
Molar incisor hypo-mineralization	
f) <i>Ageing causes</i>	Yellow
III) Internalized	
Caries	White spot, Orange, brown to black
Restorations	Brown, grey, black

Table 2 Main categories for discolouration potential of endodontic procedures

I) Intra-endodontic procedures
a) Intrinsic discolouration
b) Internalized discolouration
Root canal irrigants
Intra-canal medicaments
Endodontic filling materials
c) Intrinsic/internalized discolouration
II) Post-endodontic procedures: (<i>Internalized discolouration</i>)
Metallic posts and restorations
Improper selection/application of tooth-coloured restorations
Improper selection/application of crowns and veneers
III) Combined aetiological factors
a) Combined intra- and post-endodontic procedures
b) Combined endodontic/non-endodontic discolouration

One of the possible consequences following root canal treatment is loss of moisture content, and this may alter the light-transmitting properties of root-filled teeth (Salerno 1967). Although usually not reported, it is also associated with improper endodontic procedures

then discolouration ranging from mild to severe may occur (Tables 2–5).

Intra-endodontic procedures

Intra-endodontic procedures, including access cavity preparation, chemo-mechanical instrumentation and filling of the root canal space, may result in intrinsic or internalized tooth discolouration or a combination of both.

Intrinsic discolouration

This type of coronal discolouration occurs because of inadequate removal of coronal pulp tissue. It is usually a result of inappropriate access cavity design and/or preparation, especially when the cavity does not include the mesial and distal pulp horns (Fig. 1a). The erythrocytes, either in the remaining pulp tissue or in dentinal tubules regardless of the presence of a smear layer (Davis *et al.* 2002), will degrade into haemosiderin, haemin, haematin and haematoidin, which release iron during haemolysis (Hattab *et al.* 1999, Attin *et al.* 2003). The iron can be converted to black ferric sulphide with hydrogen sulphide produced by bacteria, and this may cause grey discolouration of the tooth crown. Apart from blood degradation, other degrading proteins of necrotic pulp tissue may also cause staining (Attin *et al.* 2003). In addition, an inadequate access cavity may complicate the clinician's ability to remove the root canal cement material from the pulp chamber while completing the root filling. Any such remaining cement is also likely to compromise the adaptation and bonding of the restorative material to the corresponding dentine walls when the access cavity is restored after the endodontic treatment.

Marin *et al.* (1997) observed the ability of blood components to penetrate dentine and induce discolouration of enamel, although it was not as pronounced as the discolouration of the coronal and radicular dentine. The authors commented that the discolouration of enamel by blood components possibly becomes more pronounced with longer exposure times. Although enamel has no tubular morphology, its organic structural features at the dentino-enamel junction, may play a role in the discolouration process.

Preventive guidelines

A well-designed and appropriately extended access cavity is essential. Successful detection, with the aid

Table 3 Summary – tooth discolouration associated with root canal irrigants

Irrigating solutions	Type of discolouration	Author/s – year
NaOCl (undiluted and 10%)	Some discolouring effect	Gutiérrez and Guzmán (1968)
1% NaOCl + 2% chlorhexidine (CHX) gel	Dark brown precipitate (Alternative irrigation)	Vivacqua-Gomes <i>et al.</i> (2002)
MTAD + NaOCl (5.25–0.65%)	Brown solution (NaOCl final rinse)	Torabinejad <i>et al.</i> (2003)
17% EDTA + 1% CHX sol.	Pink precipitate (CHX final rinse)	González-López <i>et al.</i> (2006)
2% CHX sol. + 17% EDTA	White precipitate	Rasimick <i>et al.</i> (2008)
1.54–6.15% NaOCl + MTAD	Yellow precipitate (MTAD final rinse)	Tay <i>et al.</i> (2006a) (Clinical application)
1.3% NaOCl + MTAD	Red-purple (MTAD final rinse)	Tay <i>et al.</i> (2006a) (<i>In vitro</i> study)
NaOCl + CHX sol.	Light orange to dark brown according to conc.	Basrani <i>et al.</i> (2007), Marchesan <i>et al.</i> (2007), Bui <i>et al.</i> (2008), Akisue <i>et al.</i> (2010), Krishnamurthy & Sudhakaran (2010), Nassar <i>et al.</i> (2011)
2% CHX sol. + 15% Citric acid	A white solution but returns colourless and easily removed during irrigation with CHX	Akisue <i>et al.</i> (2010)
2% CHX gel + 5.25% NaOCl	Discoloured enamel and dentine	Souza <i>et al.</i> (2011)
2% CHX sol. + 5.25% NaOCl	Discoloured dentine only	Souza <i>et al.</i> (2011)
2% CHX gel + 5.25% NaOCl + 17% EDTA	Discoloured enamel and dentine	Souza <i>et al.</i> (2011)
2% CHX sol. + 5.25% NaOCl + 17% EDTA	Discoloured dentine	Souza <i>et al.</i> (2011)

Table 4 Summary – tooth discolouration associated with intra-canal medicaments

Intra-canal medicaments	Type of discolouration	Author/s – year
Formocresol	Marked discolouration	Gutiérrez and Guzmán (1968)
CMCP (Camphorated p-monochlorophenol)	No discolouration	Gutiérrez & Guzmán (1968)
Eugenol	No discolouration	Gutiérrez & Guzmán (1968)
Iodine-potassium iodide (Iodoform-based medicaments)	Yellow to yellowish brown	Kupietzky <i>et al.</i> (2003).
Triple antibiotic therapy Ciprofloxacin Metronidazole Minocycline	Blue greyish	Kim <i>et al.</i> (2010a)
Ledermix paste Tetracycline Corticosteroid	Grey-brown	Kim <i>et al.</i> (2000a,b), Day <i>et al.</i> (2011)
UltraCal XS	Yellow	Day <i>et al.</i> (2011)

of a contra-angled (Briault) probe (Fig. 1b), and removal of any 'catch' from the roof of the pulp chamber will ensure complete removal of the pulp tissues, particularly from the mesial and distal pulp horns (Fig. 1b). Thorough irrigation of the access cavity will also help to ensure that all pulp tissue has been removed from the pulp chamber.

Internalized tooth discolouration

Many studies have reported that various materials used during root canal treatment can cause coronal tooth discolouration if they are left in the crown of the tooth during or after root canal treatment (Tables 3–5). The

various materials include irrigants, medicaments, core root filling materials and root filling cements.

Root canal Irrigants

Antimicrobial activity, dissolving of the remaining pulp tissues, lubrication during mechanical instrumentation, availability and low cost are the fundamental requirements for root canal irrigants (Zehnder 2006, Haapasalo *et al.* 2010). Whilst sodium hypochlorite (NaOCl), at varying concentrations, is the most common irrigant, other solutions have also been advocated. Some of these are used alone but most are used in combination with NaOCl, or as a final rinse to enhance the antimicrobial activity and substantivity against

Table 5 Summary – tooth discolouration associated with root canal cements

Root canal cements	Type of discolouration	Author/s – year
AH-26	Grey Grey (1st week) to grey black (12 months)* Black granular appearance (2 years)*	van der Burgt <i>et al.</i> (1986a,b) Parsons <i>et al.</i> (2001) Davis <i>et al.</i> (2002)
AH-26 silver free	Grey Moderate discolouration (9 months)*	van der Burgt & Plasschaert (1985) Partovi <i>et al.</i> (2006)
Grossman's	Orange-red	van der Burgt <i>et al.</i> (1986a,b)
Zinc oxide/eugenol	Orange-red Marked discolouration (9 months)*	van der Burgt <i>et al.</i> (1986a,b) Partovi <i>et al.</i> (2006)
EndoFill	Marked discolouration (9 months)*	Partovi <i>et al.</i> (2006)
Endomethasone	Orange-red	van der Burgt <i>et al.</i> (1986a,b)
N2	Marked (Orange-red)	Gutiérrez & Guzmán (1968) van der Burgt <i>et al.</i> (1986a,b)
Tubli-Seal	Mild pink to orange-red Moderate discolouration (9 months)*	van der Burgt <i>et al.</i> (1986a,b) Partovi <i>et al.</i> (2006)
Diaket	Mild pink	van der Burgt <i>et al.</i> (1986a,b)
Riebler's paste	Severe dark red	van der Burgt <i>et al.</i> (1986a,b)
Roth's 801 (nonstaining)	Slight (3 months), Red (12 months)* Pink with dark grey particles (2 years)*	Parsons <i>et al.</i> (2001) Davis <i>et al.</i> (2002)
Sealapex	Slight-moderate (12 months)* Light grey (2 years)*	Parsons <i>et al.</i> (2001) Davis <i>et al.</i> (2002)
Kerr Pulp Canal	Marked discolouration*	Parsons <i>et al.</i> (2001)
Sealer	Dark grey (2 years) interspersed with a dark orange*	Davis <i>et al.</i> (2002)
Apatite Root Sealer III	Slight discolouration (9 months)*	Partovi <i>et al.</i> (2006)
Epiphany	Change in tooth brightness	Shahrami <i>et al.</i> (2011)

*Smear layer was not removed.

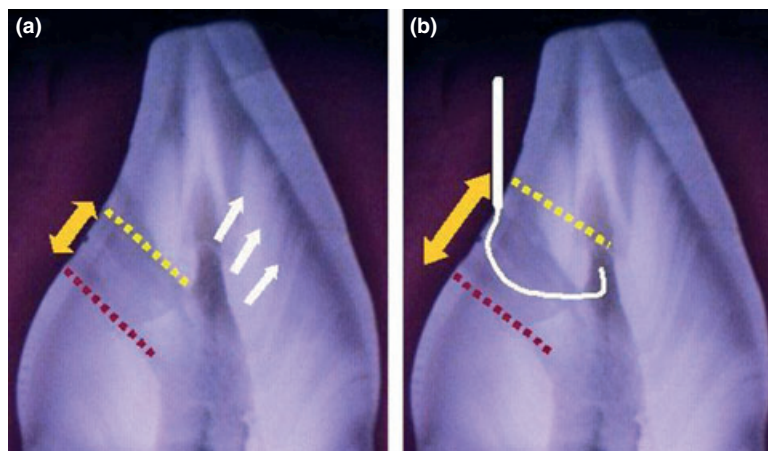


Figure 1 (a) Sectioned incisor tooth crown showing the pulp horn and dentinal tubule pattern. If pulp tissue is left in the pulp horn, then it can cause discolouration of the dentine via the tubules (white arrows). (b) Using the contra-angled probe facilitates the detection of the remaining pulp chamber roof, thus ensuring proper extension of the access cavity.

some resistant bacteria, to decrease the caustic effect or to aid in removing the smear layer (Zehnder 2006, Mohammadi & Abbott 2009, Haapasalo *et al.* 2010).

Although sodium hypochlorite is a bleaching agent and is not usually considered to cause tooth discolouration, it should be noted that NaOCl has been reported to cause dentine discolouration. This discolouration is a result of its contact with erythrocytes and its high tendency to crystallize on the root dentine, which may mean that it is difficult to completely remove from the

canal (Gutiérrez & Guzmán 1968). In addition, the combination of NaOCl with other adjunct irrigating solutions has been found to cause marked tooth discolourations (Table 3).

Vivacqua-Gomes *et al.* (2002) observed a dark brown precipitate when NaOCl was combined with chlorhexidine (CHX) gel. Other authors have reported the same type of discolouration when NaOCl has been used with CHX solutions (Basrani *et al.* 2007, Marchesan *et al.* 2007, Bui *et al.* 2008, Akisue *et al.* 2010, Krishnamurthy

& Sudhakaran 2010, Nassar *et al.* 2011, Souza *et al.* 2011) (Fig. 2a). This dark brown precipitate can stain the dentine, adhere to the floor of the pulp chamber, access cavity and root canal walls and act as a residual film that may compromise the diffusion of intra-canal medicaments into the dentine, disrupt the adhesion of the root canal filling and favour coronal restoration breakdown (Vivacqua-Gomes *et al.* 2002, Akisue *et al.* 2010) (Fig. 3). Basrani *et al.* (2007) examined this precipitate using X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (TOF-SIMS), and they found that it contains a significant amount of parachloroaniline (PCA). This substance is carcinogenic and it can further degrade to 1-chloro-4-nitrobenzene, which also is carcinogenic.

However, by using nuclear magnetic resonance (NMR), Thomas & Sem (2010) reported that mixing NaOCl and CHX did not produce PCA at any measurable quantity, but one of the CHX breakdown products may be further metabolized to PCA (Nowicki & Sem 2011).

As a result of these possible hazards, Kim *et al.* (2012) examined the chemical interaction between Alexidine (ALX), as a substitute for CHX, and NaOCl using electrospray ionization mass spectrometry (ESI-MS) and scanning electron microscopy (SEM). The results revealed that the association of ALX/NaOCl did not produce PCA or any precipitate, and the mixing solutions of ALX and NaOCl resulted in a slight discolouration ranging from light yellow to transparent as the ALX concentration decreased. In addition, this

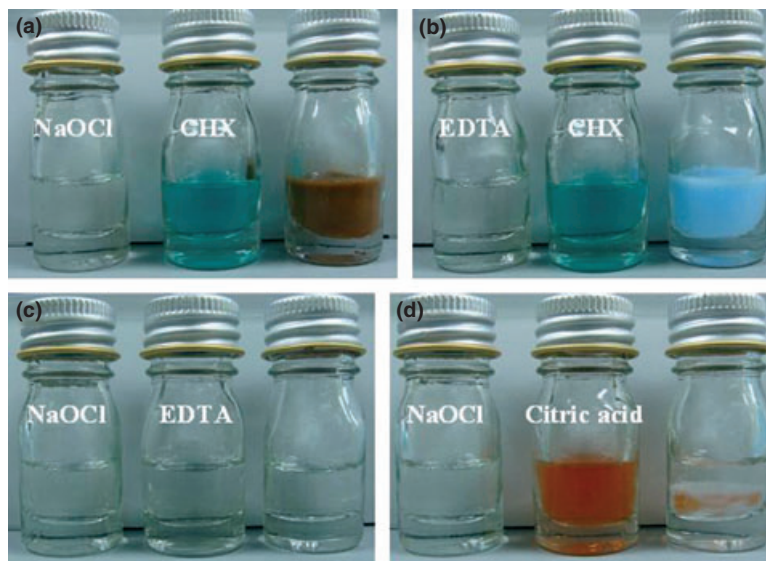


Figure 2 Discolouration when irrigants are combined. (a) 2.63% NaOCl + 2% chlorhexidine (CHX) (dark brown precipitate); (b) 18% EDTA + 2% CHX (cloudy blue); (c) 2.63% NaOCl + 18% EDTA (no discolouration); and (d) 2.63% NaOCl + 20% Citric acid (white precipitate and the solution turns cloudy after shaking).

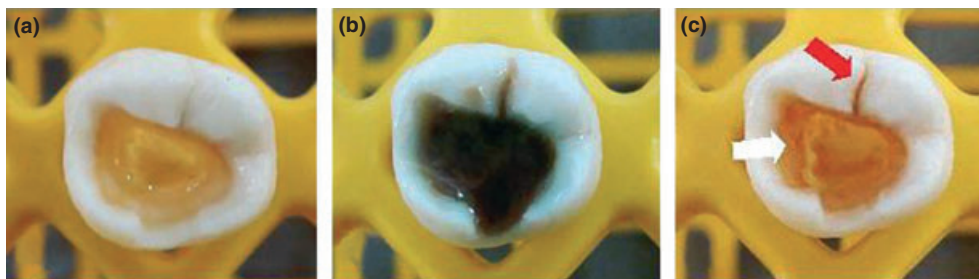


Figure 3 Discolouration potential of NaOCl/CHX combination on the access cavity walls. (a) NaOCl. (b) Dark brown precipitate after NaOCl/CHX combination. (c) The precipitate becomes adherent to the access cavity walls (white arrow) and crown fissures (red arrow) even after flushing with distilled water.

combination did not stain dentine and was easy to remove from the root canal by irrigation.

Apart from this, NaOCl has been shown to react with MTAD (a mixture of a tetracycline isomer, an acid [citric acid], and a detergent) (Dentsply Tulsa Dental, Tulsa, OK, USA), in the presence of light, causing brown discolouration (Torabinejad *et al.* 2003). This reaction may be caused by the dentinal absorption and release of the doxycycline, present in MTAD, which will be exposed to NaOCl if it is used as a final rinse after MTAD (Torabinejad *et al.* 2003).

Tay *et al.* (2006a) reported the formation of yellow precipitate along the root canal walls when NaOCl was used as an irrigant and then followed by the application of BioPure MTAD as a final rinse. They also observed red-purple staining of light-exposed, root-treated dentine when the root canals were rinsed with 1.3% NaOCl as an initial rinse followed by MTAD as the final rinse. This photo-oxidative degradation process was probably triggered by the use of NaOCl as an oxidizing agent which also resulted in partial loss of its antimicrobial substantivity (Tay *et al.* 2006a,b). It is also worth noting that the chemical reaction between NaOCl and citric acid, which leads to the formation of a white precipitate (Fig. 2d), indicates a complex interaction between NaOCl and MTAD that requires further investigations to validate the safety and usefulness of this combination of irrigants.

González-López *et al.* (2006) and Rasimick *et al.* (2008) have reported interactions between CHX and EDTA irrigants with the formation of white to pink precipitate (Fig. 2b). However, this precipitate did not show any significant amount of PCA, unlike the reaction between NaOCl and CHX.

Preventive guidelines

Practitioners should choose irrigating solutions carefully to suit the clinical condition that is being treated. Choice of irrigant should also be based on evidence from the literature. If CHX is chosen, then the insoluble dark brown precipitate, created when NaOCl and CHX are mixed, can be avoided by incorporating a thorough intermediate flush between each irrigant – this can be carried out with solutions such as saline or sterile distilled water, followed by drying of the canal before the next solution is used (Krishnamurthy & Sudhakaran 2010). Absolute alcohol has also been suggested as an intermediate flush but its biocompatibility with the periapical tissues and interactions with other irrigants remain a concern (Krishnamurthy & Sudhakaran

2010, Valera *et al.* 2010). In addition, Nassar *et al.* (2011) recommended the use of sodium ascorbate to prevent the formation of this precipitate.

Similarly, ascorbic acid solution, as a reducing agent, has been advocated as an intermediate flush between NaOCl and MTAD, to prevent the oxidation effect of NaOCl and to avoid the photodegradation of the doxycycline that is present in MTAD (Tay *et al.* 2006a). In addition, the possible interaction between NaOCl and citric acid would be avoided.

A cloudy precipitate forms when EDTA and CHX are combined. Maleic acid (MA), which has been found to be less cytotoxic and more effective in smear layer removal than EDTA (Ballal *et al.* 2009a,b), can be used as a substitute for EDTA, and the combination of MA and CHX has not shown any precipitate formation or discolouration (Ballal *et al.* 2011).

Intra-canal medicaments

Intra-canal medicaments have many clinical applications including the management of traumatized teeth, teeth with large periapical radiolucencies, inflammatory root resorption, teeth requiring apexification and regeneration/revascularization of immature permanent teeth (Banchs & Trope 2004, Jung *et al.* 2008, Shah *et al.* 2008, Mohammadi & Abbott 2009). Apart from their principle indication to help disinfect the root canal system between appointments (Haapasalo & Qian 2008), some medicaments are used as root canal filling materials for deciduous teeth (Kupietzky *et al.* 2003).

Despite these advantageous clinical applications, several medicaments can discolour teeth, especially if left for extended periods of time in the crown of the tooth. Table 4 summarizes the type of discolourations caused by intra-canal medicaments. Ledermix paste (containing demeclocycline-HCl) (Lederle Laboratories, Wolfatshausen, Germany) and triple antibiotic paste (containing ciprofloxacin, metronidazole, and minocycline) are the most common intra-canal medicaments that can induce tooth discolouration if they are not completely removed from the access cavity at a level coronal to the gingival margin, especially in immature teeth (Kim *et al.* 2000a,b, Kim *et al.* 2010a). The tetracycline derivatives in these pastes bind to calcium ions of the root dentine via chelation to form an insoluble complex (Kim *et al.* 2010a). Day *et al.* (2011) compared the discolouration potential of Ledermix paste and UltaCal XS (a radiopaque calcium hydroxide paste) (Ultradent, South Jordan, UT, USA) in replanted teeth after avulsion and found that although both

pastes resulted in tooth discolouration, the Ledermix paste exhibited an obvious colour mismatch when compared with the contralateral tooth and was significantly less acceptable to patients. However, this report did not include any details about how the pastes had been placed in the canal and whether the operators had ensured complete removal from the access cavity. Multiple operators were involved in the study so it is possible that there was little control over the application method.

The effect of sunlight on tetracycline-based medicaments has been reported as an important contributing factor in the discolouration of teeth through a photo-initiated reaction (Kim *et al.* 2000a,b). On the contrary, Kim *et al.* (2010a) observed the marked dark discolouration of tooth sections after minocycline treatment despite a lack of sunlight. However, in that study, the smear layer was removed, and this may have contributed to the extensive and accelerated staining pattern.

It is also worth noting that following the application of a triple antibiotic paste, the tooth should be adequately sealed with a suitable coronal restoration as any moisture contamination could induce a rapid dissolution of the paste and subsequent discolouration of the tooth, especially if the smear layer has been removed (Fig. 4).

Other medicaments, such as formocresol and iodoform-based medicaments, have also been reported to cause coronal discolouration (Gutiérrez & Guzmán 1968, Kupietzky *et al.* 2003). Dankert *et al.* (1976) demonstrated the ability of formocresol, especially with repeated applications, to penetrate dentine and cementum, particularly in young patients. This diffusion is attributed mainly to the small molecular composition of formocresol and the wider dentinal tubules in young patients. In addition to its discolouration potential, gingival necrosis and bone sequestration have also been reported (Cambruzzi & Greenfield 1983).

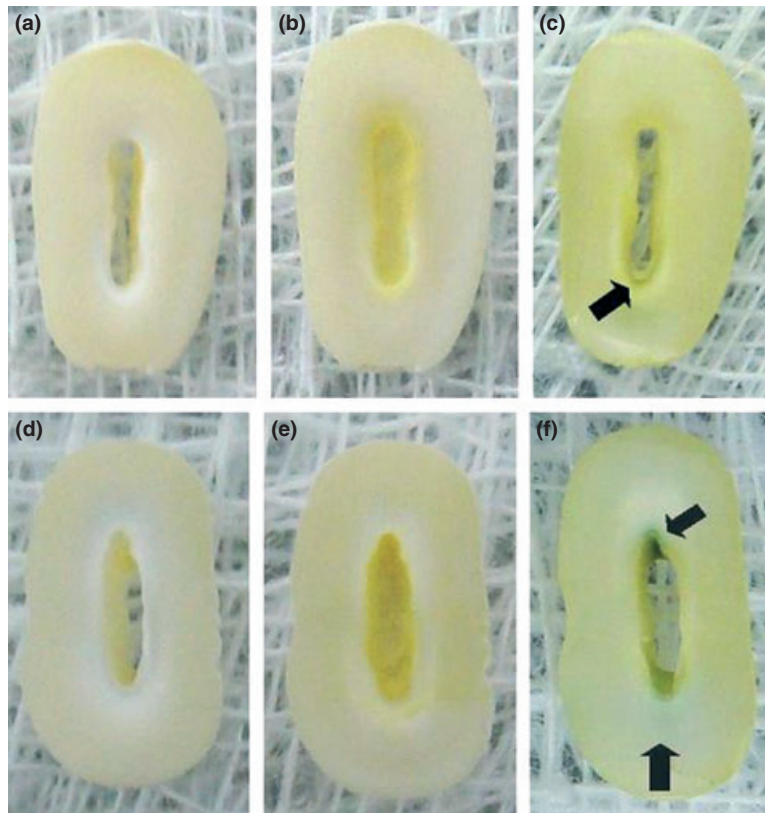


Figure 4 Effect of moisture contamination and removal of the smear layer on the penetration of triple antibiotic paste into dentine. Two root slices were sectioned from the cervical third of the root of a maxillary premolar. The chemo-mechanical instrumentation was performed using hand files and (a–c) NaOCl and (d–f) NaOCl/EDTA. After application of the triple antibiotic paste and setting, the specimens were immersed in normal saline for only 1 hour at 37 °C. Note the greater discolouration by the paste after removal of the smear layer.

Preventive guidelines

As a general and most important rule, intra-canal medicaments should be confined to the root portion of the root canal system below the gingival margin. They should not be placed in the crown portion of the tooth or in the pulp chamber to avoid coronal discolouration particularly because they have no therapeutic effect in the crown. Most medicaments are paste materials and they should be placed in the root canal in a manner that does not leave remnants in the pulp chamber. This can be easily achieved by using either delivery needles with suitable gauges (such as a NaviTip) or a spiral root filler in a low speed handpiece. When using a spiral filler, place a small amount of the paste on the spiral, insert it into the canal and then start the handpiece spinning in the forward (i.e. clockwise) direction. The spiral filler should be kept 3–4 mm short of the apical foramen and a very low speed is recommended. The spiral filler can be moved a few millimetres vertically in and out of the canal whilst still being rotated in the forward direction. If the spiral filler is kept rotating as it is removed from the canal, it will push the paste material into the canals rather than drawing it out and into the pulp chamber. The operator should remove any paste residue from the pulp chamber walls with an excavator and then wipe the pulp chamber clean with one or more (as required) cotton pellets soaked with absolute alcohol.

The application of dentine bonding or flowable resin composite to seal the dentinal tubules of the coronal dentin has been suggested as a way to prevent or reduce coronal discolouration (Reynolds *et al.* 2009, Kim *et al.* 2010a). However, this procedure is time consuming, and it is difficult to confine the bonding agent to the coronal part of the tooth and also avoid blocking the root canal.

Endodontic filling materials

The materials used for root fillings may induce tooth discolouration, particularly if left in the pulp chamber and above the gingival margin. The discolouration is usually seen in the cervical third of the crown as the overlying enamel, which is a translucent and colourless structure, is thinner in this area (Parsons *et al.* 2001, Partovi *et al.* 2006).

Silver points were historically used as a root filling material. However, it has been shown that they corroded and stained teeth as well as the surrounding soft tissues (Brady & del Rio 1975, Abou-Rass 1982). Resorcinol-formaldehyde (RF) resin therapy, commonly known as 'Russian Red' cement, has been used in some

countries as a root filling material (Schwandt & Gound 2003). Apart from its cytotoxic effects, it has been reported to cause tooth discolourations ranging from pink to deep burgundy dark colours (Matthews 2000, Schwandt & Gound 2003). Gutta-percha is the most common core filling material used throughout the world but it has been reported to cause a light pink discolouration (van der Burgt & Plasschaert 1985, Partovi *et al.* 2006). Royal *et al.* (2007) observed colour changes in Resilon pellets when disinfected with NaOCl, MTAD or CHX. Interestingly, a precipitate was also formed when immersed with the latter. The authors explained this chemical interaction was because of the presence of a dye in the Resilon material or its adsorbance to broth proteins, added in their experiment. This finding, together with its ability to biodegrade over time, is likely to have limited its adoption as a root filling material (Kim *et al.* 2010b).

Many studies have investigated the discolouring potential of root canal cements (Table 5) but several methodological differences especially by either removing the smear layer or not, and determining the colour change, by either vision or computer analysis of digital images, results in difficulties when interpreting the data. van der Burgt *et al.* (1986a,b) compared the ability of some commonly used root canal cements to induce tooth discolouration after removing the smear layer. The tooth sections showed marked penetration of the cement components into the dentinal tubules and also into the cementum. The latter suggests that some cements may also have the potential to cause periodontal irritation. van der Burgt *et al.* (1986a) and Parsons *et al.* (2001) commented that occlusion of dentinal tubules by smear layer may prevent or slow the process of cement diffusion into the tubules and discolouration. This was demonstrated by Davis *et al.* (2002) who found that cement particles did not diffuse into the dentinal tubules and was only confined to the pulp chamber whilst blood pigments showed complete diffusion and marked discolouration, despite the presence of smear layer.

Root canal cements usually cause discolouration because of the presence of unreacted components or the corrosion of some components owing to moisture and/or chemical interaction with dentine (Allan *et al.* 2001, Parsons *et al.* 2001, Walsh & Athanassiadis 2007). These findings suggest that cements inside the root canal, which do not have the same appearance when mixed on the glass slab, are more likely to undergo chemical interactions with radicular dentine, in addition to the physical changes that may occur during

setting. As an example, AH26 (Dentsply De Trey, Konstanz, Germany), an epoxy resin cement, contains bismuth trioxide as a filler and radiopacifier. As this cement sets over time, the complex environment inside the root canal system triggers a chemical interaction that results in conversion of the filler to a range of bismuth compounds, which become a green and then a black colour (Walsh & Athanassiadis 2007). In silver-containing AH26, the corrosion of silver and its possible interaction with dentine also results in grey-black discolouration (Allan *et al.* 2001, Davis *et al.* 2002). Further, the inadequate removal of AH26 during retreatment has been reported to induce intra-canal medicaments to progressively discolour the tooth (Tinaz *et al.* 2008). The modified AH-Plus epoxy resin cement (Dentsply De Trey, Konstanz, Germany) contains zirconium oxide as the radiopacifier. This substance has long-term colour stability and does not undergo the chemical reactions that bismuth does (Walsh & Athanassiadis 2007). Other root canal cements, such as Epiphany (SybronEndo, Orange, CA, USA), have also been shown to alter the brightness of teeth (Shahrami *et al.* 2011).

Mineral trioxide aggregate (MTA) is a useful material for situations such as direct pulp capping and repairing perforations. Despite the favourable biological profile, grey mineral trioxide aggregate has the ability to cause tooth discolouration, as well as discolouring the adjacent gingiva (Naik & Hegde 2005, Bortoluzzi *et al.* 2007). A nonstaining formula (white mineral trioxide aggregate) without iron oxide (FeO) (Asgary *et al.* 2005) was therefore developed for use in aesthetically sensitive areas. However, it has also been reported to cause grey discolouration of teeth (Watts *et al.* 2007, Boutsioukis *et al.* 2008, Jacobovitz & de Lima 2008, Belobrov & Parashos 2011). This is probably a result of the oxidation of some elements in the material. Some adjunct additives have been suggested to enhance the physical and antimicrobial properties of mineral trioxide aggregate (Kogan *et al.* 2006, Ahmed *et al.* 2011), but the discolouring potential of these modified formulations requires further investigations.

Preventive guidelines

Similar to intra-canal medicaments, keeping the root canal filling materials in the root portion and apical to the gingival margin of the tooth is essential. The pulp chamber must be carefully checked once the root filling has been completed. The gutta-percha can be removed with hot instruments with the remaining gutta-percha then being vertically compacted into the

root canal. The root filling cement should be cleaned from the pulp chamber by using one or more (as required) cotton pellets soaked with absolute alcohol. It is essential that this step is completed before the cement sets because the alcohol will not dissolve the set materials.

Intrinsic/internalized discolouration

Tooth discolouration resulting from intra-endodontic procedures may have a more complex pattern. Inadequate access cavity preparation may cause pulp tissue to remain as well as leading to improper coronal extension of the root filling above the gingival margin (Fig. 5a,b). As both of these factors have the potential to induce tooth discolouration, they should be considered during diagnosis and when planning root canal re-treatment.

This complex pattern can also be recognized with some endodontic materials, including intra-canal medicaments and cements, that do not have significant discolouring effects, but when combined with blood, they may induce staining because of the reactions between the material and some blood components (Gutiérrez & Guzmán 1968, van der Burgt *et al.* 1986a).

Post-endodontic procedures

Proper selection and adequate placement of post-endodontic restorations are fundamental prerequisites for successful root canal treatment and long-term retention of the tooth. When dealing with anterior teeth, aesthetics must be considered as part of the planning and selection of these restorations. Restorations with metallic materials (such as amalgam, pins and metallic posts) can induce coronal discolouration and should be avoided in such circumstances. Amalgam restorations placed to restore palatal or lingual access cavities usually lead to dark grey discolouration of the dentine because of the penetration of amalgam corrosion products into the dentinal tubules (Scholtanus *et al.* 2009). The discolouration associated with amalgam restorations is difficult to remove with bleaching and it tends to recur over time (Attin *et al.* 2003). Metallic posts may also result in discolouration even if covered with a tooth-coloured composite restoration. In addition, the resin composite may also alter its colour over time. Metallic posts are often used when the tooth is being restored with a full coverage ceramic crown restoration, but there can be some discolouration of the

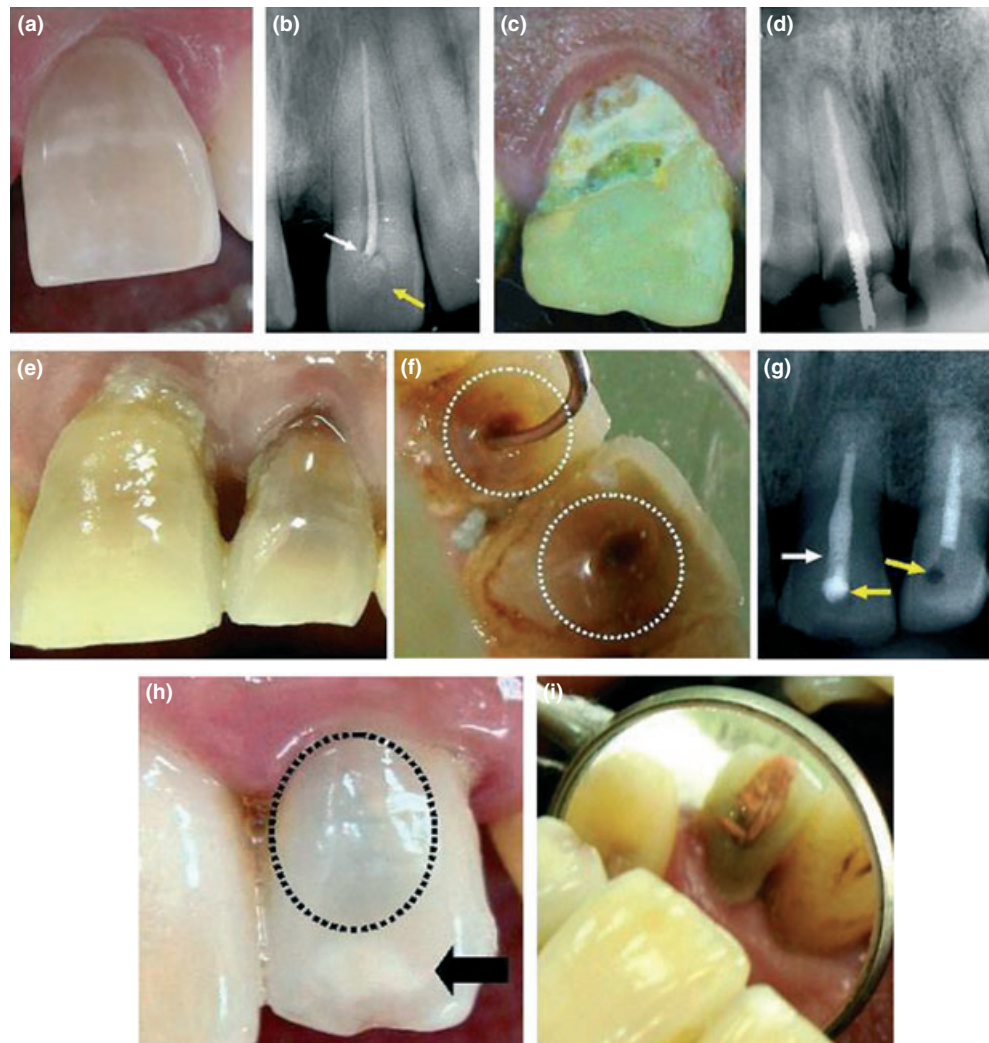


Figure 5 (a, b) Intra-endodontic procedures causing coronal discolouration of a maxillary central incisor: (yellow arrow) improper access cavity preparation and (white arrow) coronal extension of the root canal filling (Intrinsic/internalized discolouration). (c, d) Post-endodontic procedures causing discolouration (improper post- and tooth-coloured restoration with recurrent caries). (e) Coronal tooth discolouration of maxillary central and lateral incisors because of f and g (white arrow) intra-endodontic procedures (inadequate access cavity preparation and coronal extension of root canal filling). (f, g) (yellow arrows) post-endodontic procedures (inadequate coronal restorations). (h, i) Dark discolouration (circled) of the maxillary lateral incisor because of leaving the gutta-percha and cement in the crown of the tooth. Note also the intrinsic white incisal discolouration because of enamel fluorosis (black arrow).

root portion of the tooth that may be visible through the gingiva (Ferrari *et al.* 2000).

Despite the evolution of tooth-coloured restorations and recent advances for optimum colour matching, the inappropriate preparation of the tooth surface, inadequate application and the inherent limitations of the materials usually result in marginal discolouration subsequent to bacterial penetration and/or caries (Plotino *et al.* 2008, Ferracane 2011) (Fig. 5c,d). Resin

composite restorations generally discolour over time because of the complex oral environment and stains from dietary sources (Ardu *et al.* 2010, Soares-Geraldo *et al.* 2011).

Preventive guidelines

Metallic restorations, such as amalgam, should be avoided in anterior teeth following root canal treatment.

Metallic posts should only be used in teeth requiring crowns that have sufficient thickness of dentine in the root (especially on the labial aspect) plus a thick gingival biotype. Because of the high demand for post-endodontic aesthetic restorations, a variety of tooth-coloured post-systems have been developed, which can serve as viable alternatives to metallic posts.

Resin composites should be manipulated precisely to prevent undesirable consequences including marginal and/or bulk discolouration. Besides conventional visual assessment, shade selection for tooth-coloured restorations, including resin composites, laminates and ceramic crowns, can also be performed using supplemental devices such as spectrophotometers, colorimeters or other imaging systems to obtain predictable aesthetic outcomes (Chu *et al.* 2010).

Combined aetiological factors

Combined intra- and post-endodontic procedures

It is not uncommon for both intra- and post-endodontic procedural errors to occur. In such cases, accurate determination of the cause of the discolouration will enable appropriate treatment to be provided with a favourable outcome. An example is the presence of gutta-percha/cement remnants in the pulp chamber together with a defective or metallic coronal restoration. Such a tooth will require the removal of both the restoration and the root filling materials prior to bleaching, if indicated (Fig. 5e–g).

Combined endodontic/non-endodontic discolouration

In more complicated cases, tooth discolourations may be combined with other extrinsic, intrinsic or internalized stains that are not endodontic in origin (Fig. 5h,i). Extrinsic stains that can be due to either direct or indirect chromogens, such as smoking and cationic antiseptics (Sulieman 2008), should be removed first, to optimize the colour evaluation following internal bleaching. Other non-endodontic stains should be identified and removed either prior to or during the internal bleaching. Indeed, there may be diagnostic challenges and determining the exact aetiological factors could be confusing. However, examining the neighbouring teeth may be helpful as some intrinsic stains, such as enamel fluorosis, can usually be identified in more than one tooth.

Management guidelines

Proper evaluation and preparation

A thorough clinical examination, augmented by an appropriate radiographic interpretation, is mandatory for proper evaluation of a discoloured tooth caused by endodontic procedures. Improper adaptation and/or discoloured margins of coronal fillings, the presence of carious lesions and extrinsic stains, as well as the quality and coronal extension of the root filling should all be identified initially. Prior to selecting a treatment approach, it is essential to treat caries, remove extrinsic stains if present, and to polish the external crown surface to facilitate the proper identification of the final tooth shade (Attin *et al.* 2003, Plotino *et al.* 2008). When replacing defective/discoloured restorations as well as treating caries, the tooth should only be restored temporarily, unless the existing restorations or caries are the only causes of discolouration and no bleaching is required (post-endodontic procedures). Definitive restoration of the tooth should be deferred until after the normal tooth colour has been re-established via bleaching.

Selection of the appropriate treatment approach

Removal of the cause

Adequate extension of the access cavity and removal of the cause of the discolouration (e.g. remaining pulp tissue, medicament, root canal filling material or defective coronal restorations) is required before internal bleaching (Abbott 1997). The tooth should then be re-evaluated because the colour may become satisfactory once the cause has been removed. This is typically the case when the discolouring agent only acts as a dark background and has not yet penetrated into the dentinal tubules.

Internal bleaching (Walking bleach)

Internal bleaching is a simple, inexpensive and reliable treatment approach for most coronal discolourations caused by endodontic procedures (Kaneko *et al.* 2000). If internal bleaching is to be performed, then a barrier (such as Cavit), with proximal scalloping margins corresponding to the cemento-enamel junction (Abbott 1997), and adjusted 1 mm apical to the gingival margin, should be placed to protect the periodontal tissues from the chemical irritation of the bleaching agents. If required, further bleaching of the cervical part of the crown near the gingival margin can be

performed by reducing the labial portion of the barrier until satisfactory results are achieved (Fig. 6a–c). Removal of the smear layer within the access cavity prior to bleaching enhances the penetration of the bleaching agents into the dentine but this is somewhat controversial (Attin *et al.* 2003, Plotino *et al.* 2008). In some cases that are not responding to internal bleaching alone, external bleaching techniques can also be used to help improve the colour of the tooth (Fig. 6d–f).

Hydrogen peroxide (H_2O_2) and hydrogen peroxide releasing agents such as sodium perborate ($\text{NaBO}_3 \cdot n\text{H}_2\text{O}$ – ‘n’ represents the available formulations in monohydrate, trihydrate and tetrahydrate) and carbamide peroxide ($\text{CH}_6\text{N}_2\text{O}_3$) are the most commonly used bleaching agents (Attin *et al.* 2003, Zimmerli *et al.* 2010). In addition, sodium percarbonate has been suggested as a possible substitute for sodium perborate because of its high bleaching efficiency at low temperature (Kaneko *et al.* 2000). Despite its comparable *in vitro* cytotoxicity and genotoxicity to other bleaching agents, more *in vivo* investigations are required to validate its safety for clinical applications (Fernández *et al.* 2010).

Different concentrations, formulations (liquid or gel), combinations (sodium perborate/hydrogen peroxide and sodium perborate/carbamide peroxide) and

application of heat or light have been suggested in an attempt to accelerate and optimize the bleaching process (Attin *et al.* 2003, Plotino *et al.* 2008, Zimmerli *et al.* 2010). However, it should be noted that the use of bleaching agents at high concentrations (such as 30% of hydrogen peroxide) with the aid of heat (thermo-catalytic technique) increases the risk for external invasive root resorption (Dahl & Pallesen 2003), especially in traumatized or infected teeth (Heling *et al.* 1995, Plotino *et al.* 2008). In addition, these bleaching agents should be handled with care to avoid contact with the oral tissues.

Once the tooth has returned to a normal colour, the bleaching agent must be removed from the access cavity. Definitive restoration of the tooth should be delayed for at least two weeks to avoid compromising the adhesion of glass ionomer cements and resin composites to enamel and dentine which is a result of residual bleaching agents in the dentine (Abbott 1997, Plotino *et al.* 2008). Aesthetic restorations with lighter shades are recommended if the bleaching procedure has not been entirely successful (Plotino *et al.* 2008). Generally, the short- and long-term prognosis of internal bleaching is favourable and acceptable to the patient, as long as the coronal restoration is maintained with no marginal breakdown that could lead to further

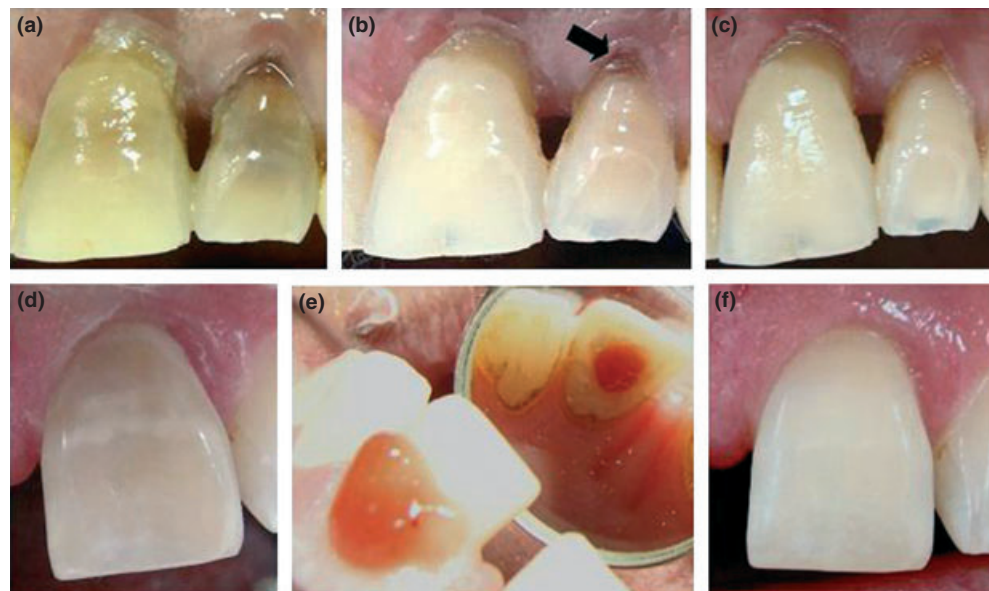


Figure 6 (a) Discoloured maxillary central and lateral incisors. (b) After two sessions of internal bleaching. The discoloration persists in the cervical area (black arrow). (c) Stepwise reduction in the labial portion of the root filling allowed adequate bleaching. The remaining yellowish-brown discoloration was left to match the colour of the root of the adjacent central incisor. (d) Discoloured maxillary central incisor. (e, f) The discoloration was persistent after two internal bleaching sessions. External/internal bleaching followed by the walking bleach technique resulted in a satisfactory outcome.

discolouration (Rotstein *et al.* 1993, Glockner *et al.* 1999, Abbott & Heah 2009). However, the outcome of managing discolouration caused by some endodontic cements and metallic restorations remains a challenge (Brown 1965, van der Burgt & Plasschaert 1986, Attin *et al.* 2003).

Other treatment options

Although internal bleaching is considered as a conservative treatment compared with other treatment approaches, in some resistant cases, it does not provide satisfactory outcomes. Hence, in such cases, more invasive aesthetic treatment such as the placement of a labial porcelain veneer or a full coverage ceramic crown may be indicated.

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Attachment A-4

Reliability of shade selection using an intraoral spectrophotometer

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Abstract In this study, we evaluate the accuracy and reproducibility of human tooth shade selection using a digital spectrophotometer. Variability among examiners and illumination conditions were tested for possible influence on measurement reproducibility. Fifteen intact anterior teeth of 15 subjects were evaluated for their shade using a digital spectrophotometer (Crystaleye®, Olympus, Tokyo, Japan) by two examiners under the same light conditions representing a dental laboratory situation. Each examiner performed the measurement ten times on the labial surface of each tooth containing three evaluation sides (cervical, body, incisal). Commission International on Illumination color space values for L^* (lightness), a^* (red/green), and b^* (yellow/blue) were obtained from each evaluated side. Examiner 2 repeated the measurements of the same subjects under different light conditions (i.e., a dental unit with a

chairside lamp). To describe measurement precision, the mean color difference from the mean metric was used. The computed confidence interval (CI) value 5.228 (4.6598–5.8615) reflected (represented) the validity of the measurements. Least square mean analysis of the values obtained by examiners 1 and 2 or under different illumination conditions revealed no statistically significant differences (CI=95%). Within the limits of the present study, the accuracy and reproducibility of dental shade selection using the tested spectrophotometer with respect to examiner and illumination conditions reflected the reliability of this device. This study suggests that the tested spectrophotometer can be recommended for the clinical application of shade selection.

Keywords Tooth color selection · Dental shade selection · Shade analysis · Spectrophotometer · Reproducibility

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Introduction

Reproducing the shade (color) of dental restorations (shade matching) according to the remaining natural dentition is a challenging aspect of dentistry. The assessment of the shade (shade selection) of natural remaining teeth is the first aspect of various factors in the process of fabricating a dental restoration. The most frequent technique for shade selection is using a dental shade guide containing tabs of various shades. This procedure depends on the individual visual perception of the observer. Additionally, it has been demonstrated that clinicians cannot duplicate their shade selections on different days [1, 2]. Variables including metamerism, illumination type, light reflection, and individual characterization of natural teeth further contribute to variability in shade selection [3–5].

These inherent characteristics of the shade selection process result in reduced predictability of a successful

shade match of the restoration to the natural tooth [6]. Clinically, this leads to increased chair time because of necessary adjustments or even remakes of the restoration until the patient is satisfied, especially in anterior aesthetic areas.

To improve shade selection via shade tabs and to enhance communication between the dentist and the dental laboratory, new designs of shade guides have been introduced and have shown improvements [7, 8], but limitations still persist in terms of color range [9]. Techniques like making a digital photograph together with a matching shade tab and communicating this to the dental laboratory are commonly used. These images show the relative shade match of the two objects to each other. However, the color reproducibility of these images for analysis is influenced by lighting conditions and the color adjustment of the screens. However, the success of the visual process still depends on the level of clinician skill and experience, which, like their matching ability, is highly variable [10].

The application of digital color imaging [11] and digitally supported instrument use [12] has the potential to eliminate the variability of conventional visual shade selection. Using an analysis software to determine the color parameters of conventional digital images produced by a digital camera was described as being equal to using a spectrophotometer system [13] and better than a conventional visual method [10, 14]. A number of digital measuring instruments are available on the market and have been tested [3, 4, 12]. Regarding the measurement and collection of data, the systems are different in terms of the size of area they are capturing. Systems that apply a multispectral camera system, compared to a one-spot device, are able to give a reliable shade gradation across different tooth regions [15]. These digital systems should theoretically improve communication with the laboratory and help obtain an accurate shade match of the restoration to the remaining teeth. They use the Commission Internationale de l'Éclairage (CIE) [16] $L^*a^*b^*$ color coordinates (L lightness, a chromaticity along the red–green axis, and b chromaticity along the yellow–blue axis). Based on such CIE $L^*a^*b^*$ parameters, data on tooth color obtained from computerized colorimetry or spectrophotometry allow for an objective mathematical comparison [17].

Studies comparing the visual (human) versus digital shade selection reveal poor agreement between these techniques and favor the instrumental and digital determination [6, 10, 15, 18–26]. However, one study demonstrated that human examiners showed a significantly higher agreement (40.2%) when compared with five digital devices [27]. The interexaminer reliability with these techniques was found to be acceptable to excellent in clinical measurements on natural teeth [23, 28, 29], dental restorations, or both [25].

Studies have been conducted to assess the final results of the entire process when using digital shade selection. Da Silva et al. [24] evaluated clinical effectiveness and showed that crowns matched with the spectrophotometer used in their study had significantly better shade matches than those using a conventional technique. These results are still influenced by the variation in the ceramic process in the laboratory, which cannot be neutralized by the initial data of the digital shade selection. Similar studies have reported on various digital measurement systems with similar positive results for the outcome of restorations [6, 10, 20–22]. The influence of a standardized or clinical environment on accuracy was evaluated with five different measuring devices by using shade tabs and natural teeth. Two of the five systems performed more reliably in the in vitro setting [30]. For visual shade selection, the light used in the environment is an important factor [5]. Because available spectrophotometers operate with an internal light source, the measurement surface is illuminated with this standardized light during capture. However, the possible influence on the degree of accuracy depends on the instrument used [25, 31, 32], type of material, opacity, texture, and translucency of the measured side [6, 33].

In order to apply digital shade selection for human teeth, the accuracy and reproducibility, as well as interexaminer reliability, must be considered. The purpose of the present study was to evaluate the reproducibility of measurements using the Crystaleye digital spectrophotometer (Olympus, Tokyo, Japan). The variables of different examiners and different illumination conditions were tested for their influence on the reproducibility of measurements.

Materials and methods

Fifteen subjects (8 men and 7 women) in need of one intact and untreated maxillary central incisor tooth were recruited for this investigation. The subjects ranged in age from 22 to 47 years, with a mean age of 26.1 years. Two examiners made ten repeated measurements of the labial surface of the tooth for each subject. One examiner was a dental technician and one was a postgraduate dental student. Every measurement involved three evaluation sides on the tooth (cervical, middle, and incisal) with the output of the values of L^* , a^* , and b^* ($n=300$) for each side. The measurements by the two examiners were made under the same light conditions, which represented a dental laboratory situation (environment A) with mixed natural and artificial light (Lumilux cool white, Osram, München, Germany). Examiner 2 repeated the measurements of the same subjects under different light conditions (environment B) (Fig. 1). Environment B represented the conditions of a dental unit situation with a chairside lamp (Kavolux, KaVo, Biberach,

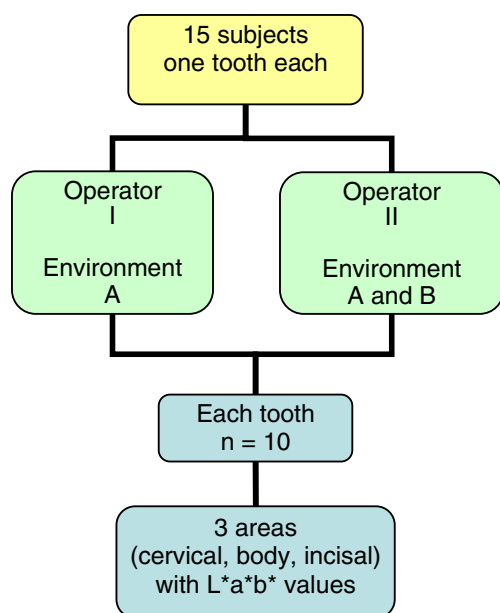


Fig. 1 Outline of the study. Fifteen subjects were measured by two operators (I and II). The measurements were repeated ten times for each tooth and in three different areas with $L^*a^*b^*$ values. Operator II performed the measurements in two different environments (A and B)

Germany) directed on the measurement side of the subject's mouth. For each measurement, all teeth were clean, no saliva was on the surface and the teeth were not dry.

The two examiners were educated and experienced with the applied digital spectrophotometer Crystaleye (Fig. 2). Prior to data acquisition of each subject, the instrument was automatically calibrated using an integrated calibration plate on the base station of the device. It uses seven light-



Fig. 2 Data acquisition with the digital spectrophotometer used in the study. The measurement was performed with a single-use cap for each patient

emitting diodes as an illumination source, with a $45^\circ/0^\circ$ geometry. The capture time is always 0.2 s. A single-use rubber contact cap was placed on the measurement tip of the device and then positioned to capture the tooth image. The device was set to have the captured tooth in focus (Fig. 3). For each of the measurements ($n=10$), the position of the device was newly selected and repositioned to generate ten different measurements of each tooth. The position of the tip was located for each measurement in such a way to assure that the three relevant areas (cervical, middle, and incisal) for the analysis were not reflecting light (Fig. 4). The tip was moved and relocated for each measurement. The three areas were selected automatically by the system and not changed (Fig. 5). The base station of the spectrophotometer was connected to a personal computer (XPS M1210, Dell, Austin, TX, USA) with the Crystaleye software (version 1.4) installed. Data transfer from the device to the computer was performed via the connected base station. The software was used to export the L^* , a^* , and b^* values of each of the three sides into an Excel® data table (Microsoft Office 2003®, Redmond, WA, USA) for the statistical analysis.

Statistical analysis

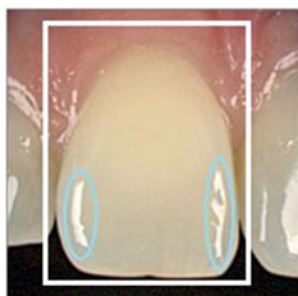
The validity of the mean color difference from the mean (MCDM) as a measure of precision was calculated as shown where each measurement is compared with the average, L^* , a^* , b^* , followed by the summation of N color differences, $\sum_{i=1}^N$, then divided by the number of measurements, N [34].

$$\text{MCDM} = \frac{\sum_{i=1}^N \left[\left(L_i^* - \bar{L}^* \right)^2 + \left(a_i^* - \bar{a}^* \right)^2 + \left(b_i^* - \bar{b}^* \right)^2 \right]^{\frac{1}{2}}}{N}$$



Fig. 3 Level of the depth of focus can be switched between tooth (T), lips (A), and facial (F) position. For the purposes of this investigation, the level of focus was selected on position T

Fig. 4 The examined tooth should be positioned inside the displayed square and with symmetrical light reflection on both sides of the measurement surface

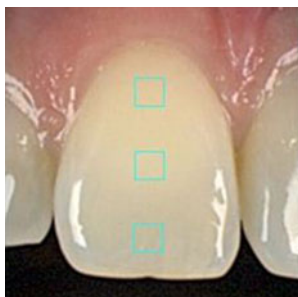


Two general linear models using generalized estimating equation techniques for correlated outcomes were fitted to the data. Each subject was considered as a single cluster. The independent correlation matrix type structure was used and only measurements from different subjects were considered to be statistically independent (PROC GENMOD, REPEATED statement; SAS 9.1, Cary, NC, USA). In the first model, the continuous response variable was modeled as a function of light, target, color space, and the corresponding interactions as explanatory variables. In the second model, the continuous response variable was modeled as a function of observer, target, color space, and the corresponding interactions as explanatory variables. Model assumptions were graphically checked by residuals and other regression diagnostics, thus the normality of error terms can be assumed.

Results

The mean of the MCDM was 5.228 (the confidence interval range, 4.6598–5.8615) of the measurements. The mean least squares means for examiner 1 was 5.2607, for examiner 2 5.1962, for the measures body 4.7166, cervical 5.4693, and incisal 5.4995. The confidence limits were 4.6598 and 5.8615 for examiner 1, 4.6727 and 5.7197 for examiner 2, 3.9332 and 5.500 for body, 4.5128 and 6.4257 for cervical, and 4.6317 and 6.3673 for incisal. The differences of least square means between examiners 1 and 2 were graphically explored with 95% confidence intervals, separately for each CIE and evaluation side. There were no statistically significant differences between

Fig. 5 Three squares in the cervical, body, and incisal areas used for color measurement. These positions were selected automatically by the system and not changed



values obtained by the two examiners or between different illumination environments.

Discussion

Digital measurement devices for dental shades, such as spectrophotometers, have proven to be a reliable improvement over conventional visual shade selection using shade tabs [3, 4, 12]. However, possible misreadings can occur due to variation in surface texture and luster, the influence of the light in the operating room, and incorrect positioning of the device. A general limitation of most digital devices is the size of the measurement probe. A large probe, such as the device used in this study, cannot be used in the posterior area. This current study was designed to test the reliability of a newly introduced spectrophotometer under different light conditions and with different operators. Therefore, no conclusion can be drawn regarding the result or quality of the shade of a dental restoration. The collected data for the statistics are based on the values of each of L^* , a^* , and b^* and not of the calculated ΔE^*_{ab} values, which provide the quantity of difference in this color system.

The type of testing environment has an influence on the evaluation and can be performed in a standardized (shade tabs) or clinical (natural teeth) environment. Dozic et al. [30] showed different results comparing these two environments. Three out of five digital devices were more reliable in an in vitro setting. Therefore, the present study was performed in a patient treatment setting as similar to everyday use as possible. One operator performed the measurements repeatedly in a laboratory with mixed light and at a different appointment with a dental unit chairside lamp shining on the measurement side. No significant difference between the two sides was found.

Interexaminer reliability is an important issue in using a measurement device that is supposed to deliver reliable results for different users. In the present study, the results of the two examiners were compared to each other. The deviation between the users was not statistically significant. Similarly, Schmitter et al. [23] reported acceptable to excellent agreement of three examiners using a spectrophotometer. However, Derdilopoulou et al. [29] showed 49.7% agreement between two examiners. Similar results were reported by Gehrke et al. [25], showing significant disagreement (45%, 18 of 40 cases) among three examiners. This indicates variability in the reliability and sensitivity for different operators and their specific handling of some of the systems.

Reproducibility is important to the precision of a spectrophotometer. Clinically, it is important to know how reliable the first measurement is. In the present study, the same tooth of one subject was repeatedly measured ten

times at the same appointment. The measurements showed no significant variation. Tung et al. [28] showed that a tested colorimeter agreed with itself 82% of the time, whereas visual selection showed 64% agreement. The agreement of the three measurements at different times was 89.6% when using a digital device.

Conclusion

Within the limits of the present study, the accuracy and reproducibility of dental shade selection using the tested spectrophotometer with respect to the examiner and illumination conditions reflected the reliability of this device. Therefore, it can be recommended for clinical application.

Conflicts of interest The authors have no conflicts of interest to declare.

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Attachment A-5

Image Calibration for Color Comparison

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Abstract - The aim is to measure the color difference between two images of the same object taken before and after a treatment that resulted in color change (such as teeth bleaching i.e. teeth treatment with different whitening products). Image calibration is a necessary component for the comparison of colors between the objects contained in the images. The two aspects of the image calibration process will be presented in this paper: position calibration of objects (studied to ensure that the comparison is performed between the same area of the objects) and color calibration (altered from the acquisition of images).

Keywords: Modeling, Visualization, Decision Support System, Computer Graphics, Image Processing, Medical Imaging.

I. INTRODUCTION

The recent technological improvement in: computers, communication networks and the Internet have greatly affected contemporary society. These improvements have translated in an ongoing improvement of dental medicine. A new generation of technologies focused on analysis, communication and color checking was developed in recent years.

Spectrophotometry, Colorimetry and Digital Image Computer Analysis are the instrumental methods used in dental practice and in research [7, 9, 10].

To perform a measurement of an objects color change due to a treatment an image will be taken before and after the treatment was performed.

For the correct color comparison of two objects, the correct timing positions (coordinates) of the objects in question, in their respective images, are needed. Furthermore, color correction of the two images (taken at different times) is needed in order to ensure accuracy (unmodified objects must have the same color and the color difference of the studied objects needs to be as close to the real difference as possible), see [5].

A color difference threshold will be established, if the difference of color between the two objects is below the established threshold the color of the tow objects is considered unchanged, otherwise it is considered that the treatment had the desired effect (the color of the object has changed).

Position calibration is required when specifying an area as an initial object, in an image, in order to know the coordinates of the area for comparison purposes.

Because processing the pair image will result in a lower quality image transformation formulas (the correlation between points in the original image I1 (see Fig. 1) and the pair of points is the pair image I2) must be found.

The difference of color pixel areas must be computed rather than the difference between color pixels themselves because neighboring pixel colors show high variability (the difference in color can be significant).

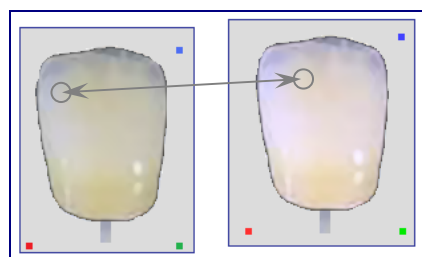


Figure 1. Correspondence zones

Color (nuance) calibration is achieved using template colors (Red, Green, Blue) shown in the two images (see Fig. 1). These marks help determine the change in position.

II. IMAGE CALIBRATION

Synchronization transformations. Two identical areas of the objects in the two images are linked by a pixel conversion formula $P(x,y)$ that enables an image pixel coordinates to obtain the corresponding $P'(x',y')$ coordinates in the other image (see Fig. 2).

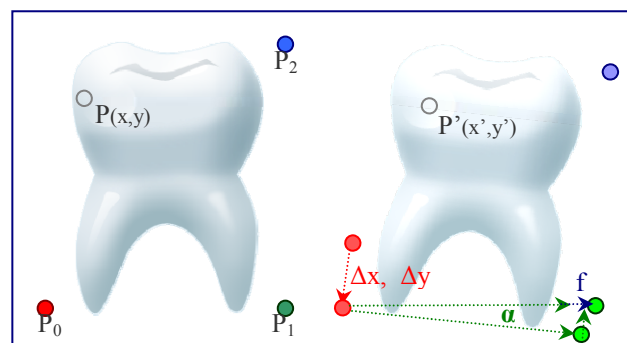


Figure 2. Determination of transformation

Three reference points (Red, Green, Blue) are necessary to determine the parameters of the transformation. To implement this we propose an expansion *Branch and Bound* algorithm applied on a point close to the three corners of where it should be placed. Starting from this point the algorithm creates a search disk on a grid by increasing the radius of the disk with a value dependant on the range size of the area searched. Once an area has been detected near the desired color the algorithm will refine the search to determine its center (see Fig. 3). The search of the critical point will be accomplished by

specifying the values of its R, G, B components and the margins of error.

Using reference coordinates (center colored areas in basic colors) the parameters of the three transformations described below ([15]) can be determined.

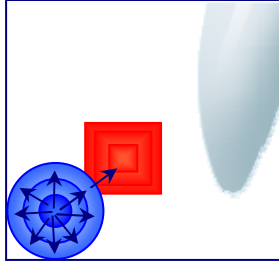


Figure 3. Determination of reference points

The first transformation represents a translation $T(\Delta x, \Delta y)$ that ensures that the P_0 points (marked with red in the bottom left part of Figure 2) overlap. The formula is given by:

$$\begin{cases} x_1 = x + \Delta x \\ y_1 = y + \Delta y \end{cases} \quad (1)$$

The second transformation represents a rotation $R(P_0, \alpha)$ that ensures that the points P_1 (marked with green in the bottom right part of Fig. 2) have the same direction. The rotation formula is given by:

$$\begin{cases} x_2 = x_1 * \cos \alpha - y_1 * \sin \alpha \\ y_2 = x_1 * \sin \alpha + y_1 * \cos \alpha \end{cases} \quad (2)$$

The last applied transformation is a horizontally applied scaling operation $S_0(f_x)$ that ensures that the points P_1 overlap. The formula is given by:

$$\begin{cases} x_3 = x_2 * f_x \\ y_3 = y_2 * f_y \end{cases} \quad (3)$$

A check at the end of the transformation that ensures that the P_2 points (marked in blue on the right above) are almost overlapping is welcome.

If the points do not overlap they have either changed positions and cannot automatically synchronize or the picture was distorted on the vertical axis which can be corrected with vertical scaling $S_v(f_y)$ (similar to the previously described horizontal scaling).

Color calibration. The color adjustment will be performed using reference points nuances (Red, Green, Blue) contained in each image.

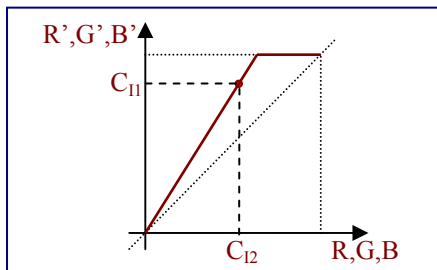


Figure 4. Changing nuances component

Each component (R, G, B) transformation will be determined so that the reference points have the same color (see Fig. 4). After the transformation the right image color component landmark (C_{12}) will be equal to the left image color component landmark (C_{11}).

Transformations for each component C (which can be either Red, Green or Blue) are given by the following formula:

$$C' = \begin{cases} C * C_{11} / C_{12} & \text{if } C * C_{11} / C_{12} \leq 255 \\ 255 & \text{if } C * C_{11} / C_{12} > 255 \end{cases} \quad (5)$$

A check at the end of the transformation that ensures that the P_2 points (marked in blue on the right above) are almost overlapping is welcome.

III. COLOR DIFFERENCE CALCULATION

The color difference ΔE^* between two colors (samples) is the geometric distance (Euclidean distance) between the corresponding points (samples) of color space [6].

This is calculated in CIE Lab system [8], using the formula:

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (6)$$

where:

ΔL^* is the difference in brightness,

Δa^* is the difference on red-green axis,

Δb^* is the difference on yellow-blue axis.

Switching from RGB to CIE Lab model is done by XYZ space in two stages as follows:

a) from RGB to CIE XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (7)$$

b) from XYZ to CIE Lab:

$$\begin{cases} L^* = 116 * (Y/Y_n)^{1/3} - 16 & \text{if } Y/Y_n > 0.008856 \\ 903.3 * Y/Y_n & \text{otherwise} \\ a^* = 500 * (f(X/X_n) - f(Y/Y_n)) \\ b^* = 200 * (f(Y/Y_n) - f(Z/Z_n)) \end{cases} \quad (8)$$

where $f(t) = t^{1/3}$ if $t > 0.008856$

$7.787 * t + 16/116$ otherwise

Due to the fact that in a picture representing the studied object area there sometimes exist significant color differences between neighbouring pixels, the color will be computed as the average of pixel colors adjacent to a predefined radius disk.

IV. TECHNICAL IMPLEMENTATION

Two classes of applications were developed. The first studies the color differences on a single image (see Fig. 5). This represents an ideal situation because the pictures of the two objects are taken simultaneously. In such applications it is preferable that the user specifies the radius of the marked area comparison disk size. Afterwards position synchronization

will be performed on the two objects such that the user must specify only the mouse cursor position in one object while the corresponding position in the other object is automatically computed.

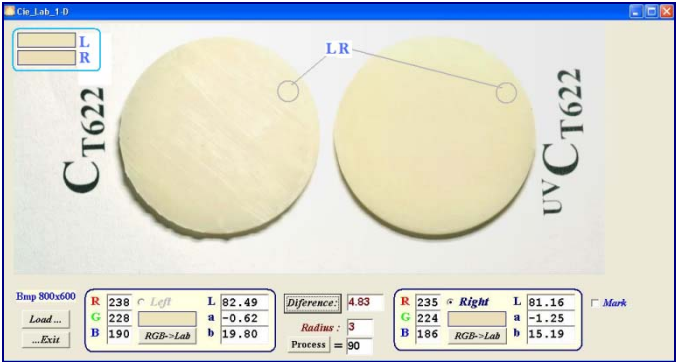


Figure 5. Comparison of a single image

For the comparison between an initial image and the image after a period of time has elapsed to be effective, then the two pictures of the objects cannot be taken at the same time. This results in two images taken at different times with different color characteristics representing the same object. This class of applications (see Fig. 6) has a greater need to synchronize the positions of the two images, so that when the user requests a color area of an image the area corresponding to the pair is automatically selected. Furthermore, due to the fact that the pictures were taken at different times color calibration must be performed.

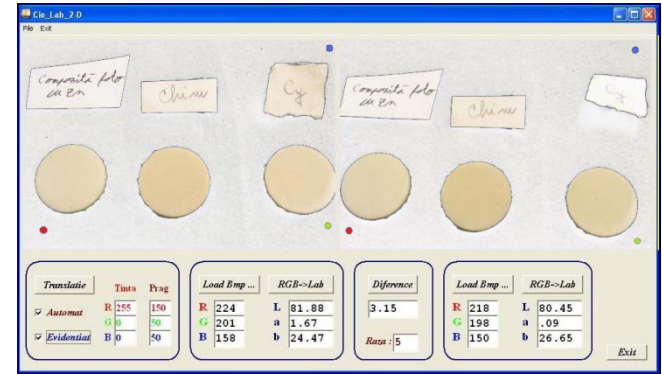


Figure 6. Comparing the two images

Studied areas can be highlighted, and their range can be specified by the user.

The comparison result is the color difference computed using the formulas described previously. Due to the fact that the images were taken at different times, color calibration is welcome.

Color Analysis. In the following section a way of looking at the staining changes throughout the object treated is presented. The first stage of the process consists of determining the object treated in the two images, more precisely the contours of the objects for each image are determined. In order to achieve this, a morphological transformation is applied (de-

scribed in [8]), see Fig. 7. *Contour determination* (δX) is done using the formula:

$$\delta X = X \setminus (X \ominus B); \tag{9}$$

This transformation marks the contour points, using the structural element G in Fig. 7.

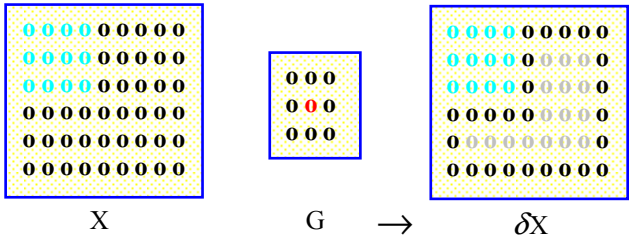


Figure 7. Contour Determination

In the above example $X \ominus G$ represents the inside of X . The contour can be computed by removing $X \ominus G$ from X .

$X \ominus B$ denotes the erosion of X by B defined as the set of all points x for which B_x (B 's translation in x , where the origin of the structuring element B (O_B) coincides with x) is included in X (see [8]):

$$X \ominus B = \{ x / B_x \subset X \}. \tag{10}$$

To perform contour extraction (which consists of big jumps in color) it is important to also look at the colors inside the object. Color analysis will be performed on a rectangular grid, built on the surface of the considered object taking into account the average color of each square (see Fig. 8).

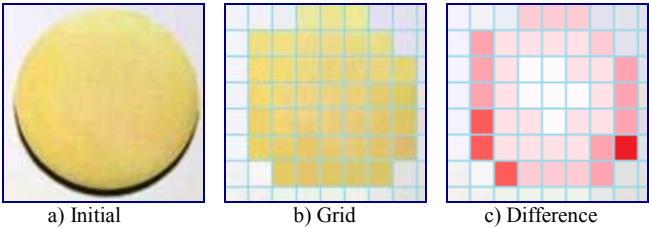


Figure 8. Colors mediation

Color differences between each pair of zones in the two images can be analyzed on a graph similar to the one shown in Fig. 9.

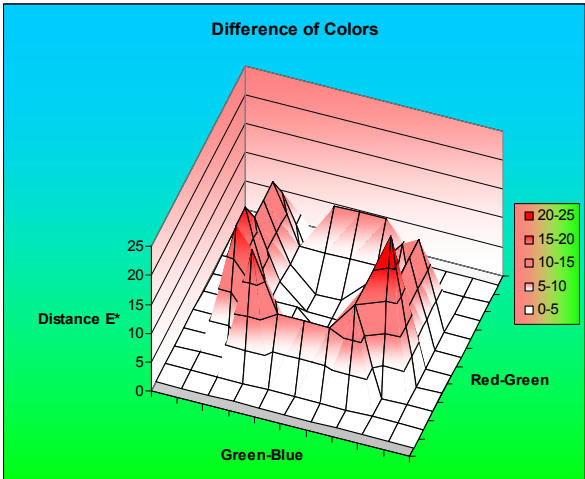


Figure 9. Differences Chart

Marking areas with significant color differences (see Fig. 10) is advised due to the fact that the naked eye (even one belonging to an experienced user) can register differences difficultly and the human eye is also vulnerable to optical illusions (colors can be misinterpreted due to their relative positions).

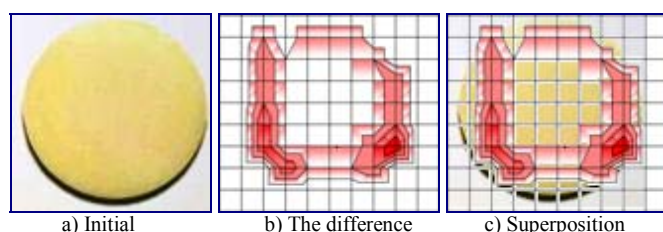


Figure 10. Marking color differences on items

In order to perform the study on the color change of objects, under certain conditions, position calibration and color calibration are needed. Automatic color difference analysis (where the user does not need to indicate the compared areas) is a primary objective of this paper. The sensitivity analysis ([12]) is likewise important because it signals outcomes significantly altered by environmental conditions in the taken images. Such a Decision Support System helps the user establish optimal treatments to obtain the desired color and furthermore (making use of sensitivity analysis, [13]) it helps determine sensitive processes (to which further attention is necessary [4]).

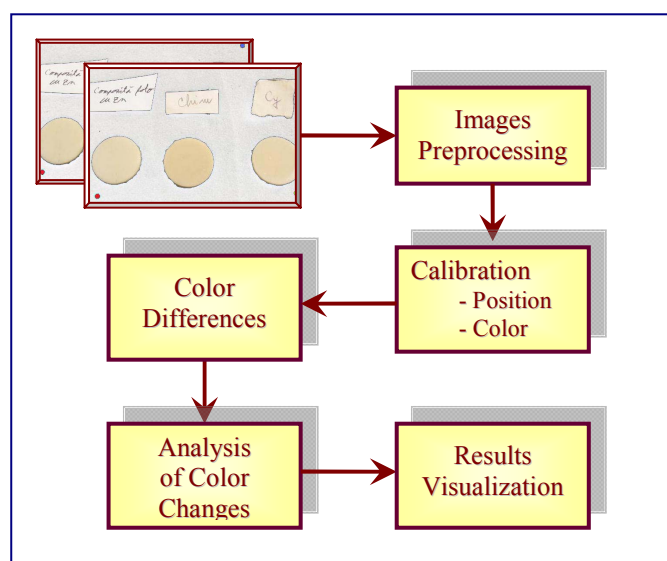


Figure 11. Stages of Change Study of Color

Comparative program testing. Instrumental methods used in color selection are based on Spectrophotometry, Colorimetry and digital image analysis [1]. In this study two of the available three methods for the evaluation of the color change of composite materials immersed in non-alcoholic colored beverages were used [2, 16]. For Spectrophotometry a UV-VIS UNICAM spectrophotmer computer was used.

Methods and materials: 64 disks of four composite resin types (n=16, Table I, Fig 12) were created.

TABLE I
COMPOSITES RESINS

Group	Product	Manufac-turer	Type of compo-site resin	Shade
1	Premise (P)	Kerr	Nanofilled	B1
2	Gradia direct (GD)	GC	Microhybrid	A1
3	Napoglass (NG)	ICRR	Experimental composite	B1
4	Radopacril (RA)	ICRR	Experimental composite	B1

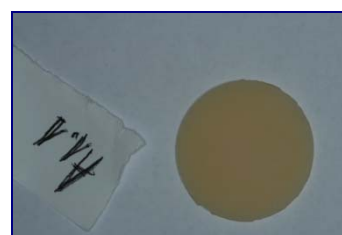


Figure 12. Composites resin specimens

Each group of the same composite resin type was further divided in four subgroups resulting in four specimens/ subgroup.

Subgroup 1 members were immersed in artificial saliva at 37°C (AS).

Each one of the **subgroup 2** elements was immersed in 50 ml of coffee (CA), prepared in a drip coffeemaker using 32 grams of ground coffee per 8 cups of water.

Subgroup 3 elements were immersed in commercial beverage A (BA), containing Azorubin (E122), Tartrasin (E102) and Brilliant Green (E142).

For **Subgroup 4** elements commercial beverage B (BB), containing Sunset Yellow (E110) and Tartrasin (E102) was used.

The composite resin specimens in subgroups two, three and four were immersed three hours a day in the colorant solution and in artificial saliva for the rest of the 21 days. Afterwards, they were rinsed in distilled water, air dried and stored in distilled water (Fig. 13).

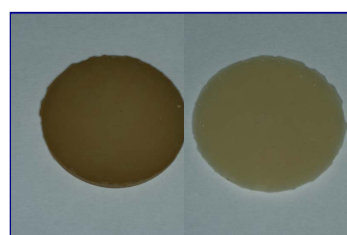


Figure 13. Composites resin specimens after immersion

Before and after the storing period, the composite samples color parameters were evaluated making use of two instrumental methods:

- The first method consists of using the computer assisted UV-VIS UNICAM spectrophotometer thus obtaining the L*, a* and b* CIELab color space values.

- The second method consists of the Computer Analysis of Data Images (CADI). Before and after coloring solution immersion images were obtained using a 100 mm f2.8 USM Canon body macro-lens MR-14Ex ring-flash Canon EOS professional camera [5]. The obtained images were then analyzed using the software developed. Two equivalent 6mm diameter round areas located in the middle of the specimen were analyzed (Fig. 14) obtaining the L^*_1 , a^*_1 , b^*_1 , L^*_2 , a^*_2 , b^*_2 values and generating the ΔE value.



Figure 14. Composite resin specimens analyzed with the software

Results. Using the first method, which was previously described, for all specimens the strongest coloring effect was obtained by immersion in coffee. Among all the specimens, the Napoglass samples registered the highest color variation. In all cases, the immersion in artificial saliva reported the lowest color variation values.

As in the first method's case for the second described method the strongest coloring effect was registered using coffee, with the exception of GD product which displayed the most powerful variation after being immersed in beverage B (containing Sunset Yellow (E 110) and Tartrazin (E 102)).

The small differences between the two instrumental methods can be explained by noting the fact that the ΔE values, obtained from the images taken before and after immersion, indicate, in the majority of groups, higher color variation than the clinically acceptable values ($\Delta E < 3.2$) [3]. No significant color differences were obtained when the samples were immersed in artificial saliva.

The results obtained with the two measuring methods were highly similar in the majority of cases.

V. CONCLUSIONS AND FURTHER WORK

The problem of color comparison is very complicated in practice due to differences in the images of the same object taken at different times. One important factor influencing the two images is environmental noise the minimising of which represents a major suggested improvement. The reduction of the influence of noise could be achieved using more efficient devices and creating special conditions in which the images are taken.

The technique for color change determination, based on digital image computer analysis, used in this paper is an accurate method that allows the determination of numerical color parameters in a predefined framework.

This method requires the obtainment of a perfectly reproducible position of the analyzed area. A standardized protocol for digital image acquisition when before and after pictures of the same object are taken is also required. Only if the requirements are met the results are relevant, otherwise the ΔE value obtained will not strictly reflect the color changes that occur in the area of reference.

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Attachment B

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Prior Art Documentation Librarian Services, LLC. (PADLS). Founded January 2018. As of August, 2022, 107 declarations have been completed for 36 law firms; four depositions were scheduled, three cancelled a few days prior, and only one was held in February, 2019.

Library Experience:

2018-present Dean Emeritus, Libraries & Norton Professor Emeritus, Purdue University
2011 - 2017 Dean of Libraries & Esther Ellis Norton Professor, Purdue University
2004 - 2011 Dean of Libraries & Professor, Purdue University, West Lafayette, IN
**2000-2004 Assistant/Associate Director for Administration, MIT Libraries,
Massachusetts Institute of Technology, Cambridge, MA.**
**1996-2000 University Librarian & Director, Falvey Memorial Library. Villanova University,
Villanova, PA.**
1978-1996 Director of Library Services, Indiana University South Bend.
**1974-1978 Associate Librarian, Indiana University Bloomington, School of Law. 1973-
1974 Instructor/Catalog Librarian. Georgia Southern College (now University).**

Teaching Experience:

**1977-1996 Associate Professor (part-time), School of Library and Information Science, Indiana
University. Subjects taught: Cataloging, Management, and Academic Librarianship.**

Education:

1972 - University of Iowa. Honors Bachelor of Arts, History, Religion & Political Science.
1973 - University of Iowa. Master of Arts in Library Science.
**1984 - Indiana University. Doctor of Philosophy. Concentration: Academic Library Administration.
Emphasis: Law Librarianship.**

Awards and Recognition:

2017 Wilmeth Active Learning Center/Library of Engineering and Science, Grand Reading Room, was announced by President Mitch Daniels, Purdue University, that it would be re-named the James L. Mullins Reading Room to honor his leadership and reputation in the academic library profession. September 2017. Portrait unveiled December 2017.

2017 Distinguished Alumnus Award by the School of Informatics and Computing, Indiana University, Bloomington. Given June 25, 2017.

2016 Hugh C. Atkinson Memorial Award, jointly sponsored by the four divisions of the American Library Association (ALA), June 27, 2016.

2015 ACRL Excellence in University Libraries Award, April 23, 2015.

Named Esther Ellis Norton Professor of Library Science by Purdue Trustees, December 11, 2011.

International Review Panel to evaluate the University of Pretoria Library, February 20 – 24, 2011. Pretoria, South Africa.

Publications: (selected)

Designing the Academic Library, Chapter Contributor. Association of College and Research Libraries, American Library Association, 2022.

A Purdue Icon: Creation, Life, and Legacy, edited by James L. Mullins, Founder's Series, Purdue University Press, 138pp., August 2017.

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"Library Publishing Services: Strategies for Success," with R. Crow, O. Ivins, A. Mower, C. Murray-Rust, J. Ogburn, D Nesdill, M. Newton, J. Speer, C. Watkinson. *Scholarly Publishing and Academic Resources Coalition (SPARC)*, version 2.0, March 2012.

"The Changing Definition and Role of Collections and Services in the University Research Library." *Indiana Libraries*, Vol 31, Number 1 (2012), pp.18-24.

"Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?" *Journal of Library Administration*. Volume 52, Issue 1, 2012, p. 124-132

Baykoucheva, Svetla. What Do Libraries Have to Do with e-Science?: An Interview with James L. Mullins, Dean of Purdue University Libraries. *Chem. Inf. Bull.* [Online] 2011, 63 (1), 45-49. <http://www.acscinf.org/publications/bulletin/63-1/mullins.php> (accessed Mar 16, 2011).

“The Challenges of e-Science Data-set Management and Scholarly Communication for Domain Sciences and Technology: a Role for Academic Libraries and Librarians,” chapter in, *The Digital Deluge: Can Libraries Cope with e-Science?*” Deanna B. Marcum and Gerald George, editors, Libraries Unlimited/Teacher Ideas Press, 2009. (a monograph publication of the combined proceedings of the KIT/CLIR proceedings).

“Bringing Librarianship to e-Science,” *College and Research Libraries*. vol. 70, no. 3, May 2009, editorial.

“The Librarian’s Role in e-Science” *Joho Kanri (Journal on Information Processing and Management)*, Japan Science and Technology Agency (formerly Japan Information Center of Science and Technology), Tokyo, Japan. Translated into Japanese by Taeko Kato. March 2008.

The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians,” KIT (Kanazawa Institute of Technology)/CLIR (Council of Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Developments in e-science status quo and the challenge, The Japan Foundation, 2007.

“An Administrative Perspective,” Chapter 14, *Proven Strategies for Building an Information Literacy Program*, Susan Curzon and Lynn Lampert, editors, Neal-Schuman Publishers, Inc., New York, 2007. pp. 229-237.

Library Management and Marketing in a Multicultural World, proceedings of the IFLA Management and Marketing (M&M) Section, Shanghai, China, August 16-17, 2006, edited. K.G. Saur, Munchen, Germany, June 2007. 390 pp.

Top Ten Assumptions for the Future of Academic Libraries and Librarians: a report from the ACRL Research Committee, with Frank R. Allen and Jon R. Hufford. *College & Research Libraries*, April 2007, vol.68, no.4. pp.240-241, 246.

To Stand the Test of Time: Long-term Stewardship of Digital Data Sets in Science and Engineering. A report to the National Science Foundation from the ARL Workshop on New Collaborative Relationships: the Role of Academic Libraries in the Digital Data Universe. September 26-27, 2006, Arlington, VA. p.141. <http://www.arl.org/bm~doc/digdatarpt.pdf>

“Enabling Interaction and Quality in a Distributed Data DRIS,” *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS. Leuven University Press, 2006. pp.55-62. Editors: Anne Garns Steine Asserson and Eduard J. Simons.

"Standards for College Libraries, the final version approved January 2000," prepared by the ACRL College Libraries Standards Committee (member), *C&RL News*, March 2000, p.175-182.

"Standards for College Libraries: a draft," prepared by the ACRL College Libraries Section, Standards Committee (member), *C&RL News*, May 1999, p. 375-381.

"Statistical Measures of Usage of Web-based Resources," *The Serials Librarian*, vol. 36, no. 1-2 (1999) p. 207-10.

"An Opportunity: Cooperation between the Library and Computer Services," in *Building Partnerships: Computing and Library Professionals*. Edited by Anne G. Lipow and Sheila D. Creth. Berkeley and San Carlos, CA, Library Solutions Press, 1995. p. 69-70.

"Faculty Status of Librarians: A Comparative Study of Two Universities in the United Kingdom and How They Compare to the Association of College and Research Libraries Standards, " in *Academic Librarianship, Past, Present, and Future: a Festschrift in Honor of David Kaser*. Englewood, Colorado; Libraries Unlimited, 1989. p. 67-78. Review in: *College & Research Libraries*, vol. 51, no. 6. November 1990, p. 573-574.

Presentations: (Representative)

“How Long the Odyssey? Transitioning the Library and Librarians to Meet the Needs and Expectations of the 21st Century University,” David Kaser Lecture, School of Informatics & Computing, Indiana University, Bloomington, IN, November 16, 2015.

Presentation at University of Cape Town, Cape Town, South Africa, August 20, 2015.

“The Challenge of Discovering Science and Technology Information,” Moderator, International Federation of Library Associations (IFLA) Science and Technological Libraries Section Program, Cape Town, South Africa, August 18, 2015.

“An Odyssey in Data Management: Purdue University,” International Federation of Library Associations (IFLA) Research Data Management: Finding Our Role – A program of the Research Data Alliance, Cape Town, South Africa, August 17, 2015.

Presentation at University of Pretoria, Pretoria, South Africa, August 11, 2015.

Co-Convener with Sarah Thomas, Harvard University, at the Harvard Purdue Symposium on Data Management, Harvard University, Cambridge, MA, June 15-18, 2015.

“Strategic Communication,” panel discussion on the Director's role and perspective on library communications at Committee on Institutional Cooperation (CIC) Center for Library Initiatives (CLI) Annual Conference, University of Illinois Urbana-Champaign, May 20, 2015.

“Issues in Data Management,” panel discussion moderated by Catherine Woteki, United States Undersecretary for Research, Education & Economics at 20th Agriculture Network Information Collaborative (AgNIC) Annual Meeting in the National Agricultural Library, Beltsville, MD, May 6, 2015.

“Active learning/IMPACT & the Active Learning Center at Purdue University,” Florida Institute of Technology, Melbourne, FL, February 11, 2015.

“Science+art=creativity: libraries and the new collaborative thinking,” panel moderator, International Federation of Library Associations (IFLA) 80th General Conference and Assembly, Lyon, France, August 19, 2014.

“Purdue University The Active Learning Center—A new concept for a library,” Association of University Architects 59th Annual National Conference, University of Notre Dame, South Bend, IN, June 23, 2014.

“Big Data & Implications for Academic Libraries,” keynote speaker, Greater Western Library Alliance (GWLA) Cyber-infrastructure Conference, Kansas City, MO, May 28, 2014.

“Research Infrastructure,” panel moderator, Association of Research Libraries (ARL) 164th Membership Meeting, Ohio State University, Columbus, OH, May 7, 2014.

“An Eight Year Odyssey in Data Management: Purdue University,” International Association of Scientific and Technological University Libraries (IATUL) 2013 Workshop Research Data Management: Finding Our Role, University of Oxford, UK, December 2013.

“Purdue University Libraries & Press: from collaboration to integration,” Ithaka Sustainable Scholarship, The Evolving Digital Landscape: New Roles and Responsibilities in Higher Education, libraries as publishers, New York, New York, October 2013.

“Tsinghua and Purdue: Research Libraries for the 21st Century,” Tsinghua University, Tsinghua, China, August 2013.

“Purdue Publishing Experience in the Libraries Publishing Coalition,” Association of American University Presses Annual Meeting, Press-Library Coalition Panel, Boston, Massachusetts, June 21, 2013.

“Indiana University Librarians Day: Purdue University Libraries Ready for the 21st Century,” Indiana University Purdue University Indianapolis (IUPUI), June 7, 2013.

“Purdue University Libraries and Open Access; CNI Project Update,” Coalition for Networked Information, San Antonio, TX, April 5, 2013.

Memorial Resolution, honoring Joseph Brannon, to the Board of the Association of College & Research Libraries, Seattle, WA, January 2013.

“An overview of sustaining e-Science collaboration in an Academic Research Library—the Purdue experience,” Duraspace e-Science Institute webcast, October 17, 2012.

“The Role of Libraries in Data Curation, Access, and Preservation: an International Perspective,” Panel Moderator, 78th General Conference and Assembly, International Federation of Library Associations, Helsinki, Finland, August 15, 2012.

“21st Century Libraries,” moderator of First Plenary Session, International Association of Technological University Libraries 33rd Annual Conference, Singapore, June 4, 2012.

“Planning for New Buildings on Campus,” panel presenter, University of Calgary Building Symposium on Designing Libraries for the 21st Century, Calgary, Alberta, Canada, May 17, 2012.

“Data Management and e-Science, the Purdue Response.” Wiley-Blackwell Executive Seminar-2012, Washington, DC, March 23, 2012.

“An overview of Sustaining e-Science Collaboration in Academic Research Libraries and the Purdue Experience.” Leadership & Career Development Program Institute, Association of Research Libraries (ARL). Houston, TX, March 21, 2012.

“An overview of Data Activities at Purdue University in response to Data Management Requirements.” Coalition for Academic Scientific Computation (CASC). Arlington, VA, September 8, 2011.

“Getting on Track with Tenure,” Association of College and Research Libraries (ACRL) Research Program Committee. Washington, DC, June 26, 2011.

“Integration of the Press and Libraries Collaboration to Promote Scholarly Communication,” Association of Library Collections & Technical Services (ALCTS) Scholarly Communication Interest Group – American Library Association, New Orleans, Louisiana, June 25, 2011.

“Cooperation for improving access to scholarly communication,” with N. Lossau (Germany), C. Mazurek (Poland), J. Stokker (Australia), panel moderator and presenter, Second Plenary Session, International Association of Scientific and Technological University Libraries (IATUL) 32nd Conference 2011, Warsaw, Poland. May 29-June 2, 2011.

“Riding the Wave of Data,” STM Annual Spring Conference 2011. Trailblazing & transforming scholarly publishing 2011. Washington, D.C., April 28, 2011.

“Confronting old assumptions to assume new roles: physical and operational integration of the Press and Libraries at Purdue University,” keynote speaker, 2011 BioOne Publishers & Partners Meeting. Washington, D. C., April 22, 2011.

“Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?” University of Oklahoma Libraries Seminar, March 4, 2011, Oklahoma City, Oklahoma.

“The Future Role of University Librarians,” the University of Cape Town, South Africa, February 25, 2011.

“New Roles for Librarians: the Application of Library Science to Scientific/Technical Research – Purdue University – a case study. International Council for Science and Technology (ICSTI); Ottawa, Canada. June 9, 2009.

“Reinventing Science Librarianship: Models for the Future,” Association of Research Libraries / Coalition for Networked Information. October 16-17th, 2008, Arlington, VA. Moderator and convener of Data Curation: Issues and Challenges.

“Practical Implementation and Opportunities Created at Purdue University,” African Digital Curation Conference, Pretoria, South Africa, (live video transmission), February 12, 2008.

Keynote speaker. “*Scholarly Communication & Academe: The Winter of Our Discontent*,” XXVII Charleston Conference on Issues in Book and Serial Acquisition, Charleston, South Carolina. November 8, 2007.

Keynote speaker. “*Enabling Access to Scientific & Technical Data-sets in e-Science: a role for Library and Archival Sciences*,” Greater Western Library Alliance (GWLA), Tucson, Arizona. September 17, 2007. A meeting of library directors and vice presidents for research of member institutions.

“*The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians*,” KIT (Kanazawa Institute of Technology)/CLIR (Council of

Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Invited to participate by the Deputy Librarian of Congress.

International Association of Technological University Libraries (IATUL), Stockholm, Sweden. June 8, 2007. Invited paper, *Enabling International Access to Scientific Data-sets: creation of the Distributed Data Curation Center (D2C2)*.

“A New Collaboration for Librarians: The Principles of Library and Archival Sciences Applied to the Curation of Datasets,” Symposium of the Libraries and the College of Engineering, University of Louisville, April 6, 2007.

“Purdue University Libraries: Through Pre-eminent Innovation and Creativity, Meeting the Challenges of the Information Age,” Board of Trustees, Purdue University, February 15, 2007.

ARL Workshop on New Collaborative Relationships: The Role of Academic Libraries in the Digital Data Universe, September 26-27, 2006, Arlington, VA. Invited participant.

NARA and SDSC: A partnership. A panel before the National Science Foundation, June 27, 2006. Arlington, VA. Invited participant.

“Kaleidoscope of Scientific Literacy: fusing new connections,” with Diane Rein, American Library Association, Association of College and Research Libraries, Science & Technology Section, Annual Conference, New Orleans, June 26th, 2006.

“Leadership for Learning: Building a Culture of Teaching in Academic Libraries – an administrative perspective,” American Library Association, Association of College and Research Libraries, Instruction Section, Annual Conference, New Orleans, June 25th, 2006.

“Building an interdisciplinary research program in an academic library: how the Libraries’ associate dean for research makes a difference at Purdue University,” International Association of Technological University Libraries (IATUL), Porto, Portugal, May 23rd, 2006.

“Enabling Interaction and Quality in a Distributed Data DRIS,” *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS, Bergen, Norway, May 12th, 2006, Brandt, and Witt presented in person

“Interdisciplinary Research,” with D. Scott Brandt, Coalition for Networked Information (CNI) Spring Meeting: Project Briefing, Washington, D.C., April 3rd, 2006.

“An Interview with Purdue’s James Mullins,” a podcast submitted by Matt Pasiewicz, on *Educause Connect*, http://connect.educause.edu/James_L_Mullins_Interview_CNI_2005

"Managing Long-Lived Digital Data-sets and their Curation: Interdisciplinary Policy Issues," Managing Digital Assets Forum, Association of Research Libraries (ARL), Washington, D.C., October 28th, 2005.

"The Odyssey of a Librarian." Indiana Library Federation (ILF), District 2 Meeting, South Bend, Indiana. October 4th, 2005.

"New College Library Standards," Standards Committee Presentation, ALA, Chicago, July 7, 2000. SUNY Library Directors, Lake George, New York. "*The College Library Standards: a Tool for Assessment.*" April 5, 2000.

Tri-State College Library Association, *Finding You Have Talents You Never Knew You Had*, Penn State Great Valley, March 25, 2000.

Using Web Statistics, American Library Association, New Orleans, June 24, 1999.

Keynote speaker at the JSTOR Workshop, January 29, 30, 1999. University of Pennsylvania, Philadelphia, PA.

"The New Standards for Electronic Resources Statistics," Society of Scholarly Publishers, Washington, D.C., September 17, 1998.

"Evaluating Online Resources: Now that you've got them what do you do?," joint presenter with Chuck Hamaker, LSU, at the NASIG Conference, Boulder, Colorado. June 1998.

"What Employers Are Looking for in New Librarians?" Pennsylvania Library Association, Philadelphia. September 26, 1997.

"The Theory of Matrix Management" panel presentation of the Comparative Library Organization Committee of the Library Organization and Management Section of the Library Administration and Management Association, a division of the American Library Association, Annual Meeting, Chicago, June 24, 1990.

Professional Involvement: (summary of recent emphasis)

The focus for my professional involvement and research has moved recently toward managing massive data-sets. This has resulted in working with faculty in the sciences and technology to determine how librarians can collaborate in managing, curating, and preserving data-sets for future access and documentation. This has included various speaking opportunities as well as participation in planning with the National Science Foundation (NSF) on ways in which librarians can be integrated more completely into the funded research process. Participation in the Kanazawa Institute of Technology/Council of Library Resources Roundtable was particularly rewarding and provided new opportunities to share with international colleagues the issues surrounding data-set management. I was

the champion for the creation of the Distributed Data Curation Center (D2C2) at Purdue University (<http://d2c2.lib.purdue.edu/>)

Throughout my career, beginning with my dissertation, I have been actively involved with assessing and evaluating libraries. In the fall of 1999, I contacted twenty-two academic library directors to determine whether the need was also felt by others. The response was overwhelmingly affirmative. This resulted in a meeting at ALA Midwinter, January 2000. A formal meeting followed at Villanova University in April 2000. As convener, I helped to form the University Libraries Group (ULG), modeled after the Oberlin Group for college libraries. The ULG is made up of university libraries that support diverse wide-ranging programs through doctoral level and have a level of support that places them in the top tier of academic institutions. A few of the member libraries, along with Villanova, are William and Mary, Wake Forest, Lehigh, Carnegie-Mellon, Tufts, Marquette, Miami of Ohio, and Southern Methodist. In 1994 appointed to the Standards Committee, College Section, Association of College and Research Libraries. During the next six years, the Committee concentrated on changing the focus of the standards from quantitative analysis of input and output factors to emphasis on assessment of the outcome. Culmination of the work was a re-issue of the *Standards for College Libraries* in 2000. The knowledge gained through my work experience enabled me to formulate the changes needed in the standards. This work allowed for close collaboration with accrediting agencies, both professional and regional. During this same time another focus emerged, the impact of digital resources. Through my work on the JSTOR Statistics Task Force, standards were developed on the collection of use of electronic databases. This Standard was later adopted in 1998 by the International Consortium of Library Consortia (ICOLC). In 2002, the American Library Association appointed me to serve as the liaison to the Marketing and Management Section of the International Federation of Library Associations (IFLA).

Professional Service: (representative list)

Nominations Committee, Association of Research Libraries (ARL), 2016.

Steering Committee, Scholarly Publishing and Academic Resources Coalition (SPARC), 2016 – 2017.
“Excellence in Library Services,” Chair, Review Team, University of Hong Kong, Hong Kong, August 24-27, 2015.

Chair, Management Advisory Board, 2015-2017; Member, Scientific Advisory Board, arXiv, Cornell University, 1/1/2013 – present.

Advisory Board for the Wayne State University School of Library and Information Science, July 2012 – present.

Advisory Board for Microsoft Academic Search, 2012 – 2015. Redmond, WA.

Transforming Research Libraries, a Strategic Direction Steering Committee of the Association of Research Libraries (ARL), 2012-2015.

Science and Technology section, representing ARL, International Federation of Library Associations (IFLA), Chair, 2013 – 2017; Member, 2011 to present.

Member of University of Pretoria, South Africa, Library Review Committee. August 2013.

Co-chair, Local Arrangements Planning Committee for 2013 Conference, Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA).

Association of Research Libraries Leadership & Career Development Program Mentor, 2011-2017.

e-Science Task Force, Association of Research Libraries. July 2006 – present. Chair, October 2011 – October 2012.

Board of Directors, International Association of Technological University Libraries (IATUL). January 2008 – December 2014.

Midwest Collaborative for Library Services (MCLS); Board Member, October 2010 – December 2012.

Chair, Library Directors, Committee on Institutional Cooperation (CIC), July 2010 – June 2012.

Board of Directors, Association of Research Libraries (ARL); October 2008 – October 2011.

Scholarly Communication Steering Committee, Association of Research Libraries (ARL) 2008-2011.

Editorial Board, *College and Research Libraries*, Association of College and Research Libraries, American Library Association. January 2008 – December 2014.

Chair, Organizing Committee for IATUL Conference 2010, June 21-24, 2010, Purdue University, West Lafayette, Indiana/Chicago, Illinois.

Conference Planning Committee for National Conference of the Association of College and Research Libraries, 2009, Seattle, Washington.

Research Committee, Association of College and Research Libraries, ACRL, division of ALA. 2002-2007, chair, 2005-2007.

Association of Research Libraries, Search and Screen Committee, Executive Director. March – January 2008.

Center for Research Libraries, Board of Directors. April 2006 – April 2012.

Academic Libraries of Indiana, Board of Directors, 2004 – present. Vice-president, 2005-2007.

President, 2007- 2009.

ALA Representative to the International Federation of Library Associations (IFLA), Marketing and Management (M&M) Section, initial term 2003-2007, re-appointed for second term, 2007-2011.

Invited to represent Research Libraries at the ACRL/3M Wonewok Retreat to assess Marketing of Academic Libraries, October 2002.

Hugh A. Atkinson Award Committee, LAMA Representative, ALA, 2001-2005.

Program Committee, Library Administrators and Management Association (LAMA), a division of ALA. 1996-2001.

ACRL, Standards and Accreditation Committee, a division of ALA. Liaison to RBMS Section of ACRL. 1997-2002.

Elected to the Executive Committee of LAMA, LOMS, a division of the American Library Association, 1998-2000. Nominated as Chair/Elect for 2003 – 2005.

Columbia University Press Advisory Committee. 1996 - 2000.

LITA/LAMA Conference Evaluation Committee, Pittsburgh, Pennsylvania, October 1996.

"New Learning Communities," Coalition for Networked Information, Indianapolis. November 19-21, 1995. Facilitator for invitational, national conference committed to developing collaborative learning and teaching techniques, involving librarians.

Planning Committee-Evaluation. LITA/LAMA 1996 Conference, Pittsburgh. This first conference, to be held jointly between two divisions of ALA, will focus on new technologies within libraries.

Indiana Cooperative Library Services Authority (InCoLSA), elected to Executive Committee, April 1991, served as President in 1993-94. InCoLSA is a statewide network of academic, public, school, and special libraries that supports library cooperation for cataloging, interlibrary loan, collection development and application of new technologies.

Governor's Conference on Libraries and Information Services. Served on Planning Committee, Academic Libraries Representative, appointed by the Governor to represent academic libraries in Indiana, Chair, Finance Committee, April 1989-July 1991.

Indiana Library Endowment Foundation Board, 1984-92. Charter Member, 1984, President, 1988-1992. 2004-2005.

University Service: (Summary)

Served on search and screen committees for senior positions including chancellor, dean, and directors; most recently I have been asked to serve on the search committee for the provost of Purdue University. At MIT service included the Library Council & appointment to the Administrative Council by President

Vest, 2001-2003 & Member of the Faculty Committee on the Library System. At Purdue appointed by the President to the Search Committee for the Provost, October 2007 to May 2008; member of the Capital Projects Committee, and IT Operational Oversight Committee as senior academic dean, 2008-2014.

Global Council, Global Policy Institute, 2012 – 2016.

Academic Program Excellence and Rankings (APER) project team, 2014.

Representative of the Academic Deans on the Re-engineering Business Operations, Purdue University, 2016 –

Academic Deans Council chaired by Provost – 2004 – 2017.

University Promotion and Tenure Committee – 2006 – 2017.

"Outstanding Team Award, Electronic Reserve Project," served as Chair, recognition awarded by the President of Villanova University to one team who made an outstanding contribution to the operations of the University, selected by a committee of administrators, faculty, and staff. Awarded September 9, 1999.

Nominated for the IUSB Lundquist Award, 1995 & 1996. The Lundquist award is given to faculty who have "exhibited excellence in teaching, scholarly or artistic achievement, and diversified relevant service..."