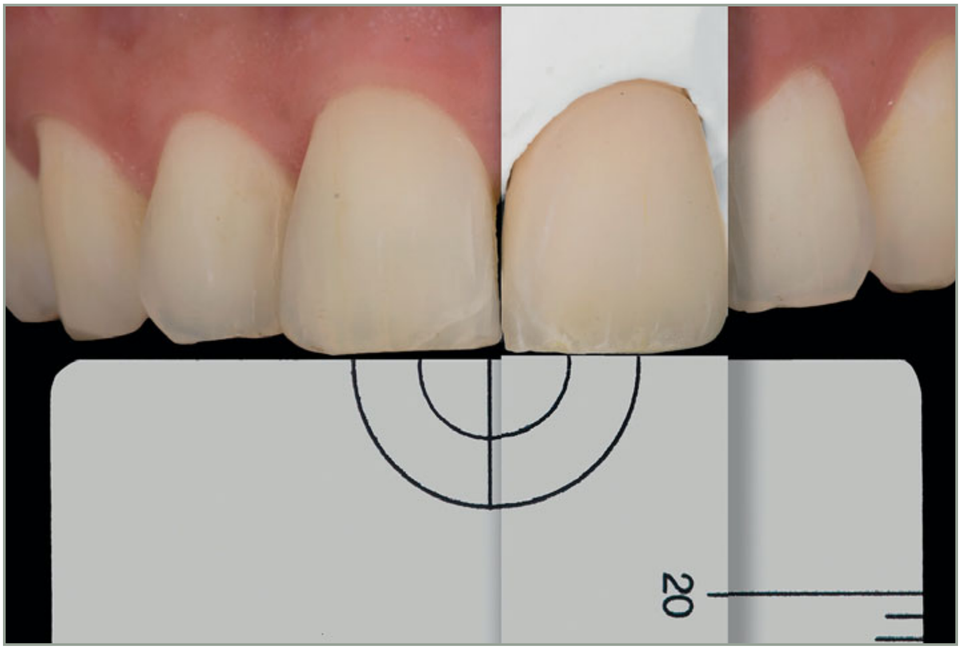
eLABor_aid: a new approach to digital shade management

Sascha Hein, Mr
Private Dental Laboratory, Germany

Javier Tapia, Dr
Private Practice, Madrid, Spain

Panaghiotis Bazos, Dr
Private Practice, Aigio, Greece



Correspondence to: Mr Sascha Hein
Private Dental Laboratory, Herrenstrasse 1, 79098 Freiburg im Breisgau, Germany;
Tel.: 0049 171 57834551, Email: s.hein@bio-emulator.com

Abstract

Contemporary dental patients present with high expectations and demand seamless optical integration of restorative interventions. As a result, clinicians and technicians are required to develop methodologies that remain practical yet increase the accuracy and objectivity of shade analysis and estimation. There have been significant advances in digital technologies over the past 20 years, with digital photography being at the forefront. Digital photography has made an immediate and profound impact on applied clinical dentistry, primarily due to instantaneous image visualization and distribution. However, standardization protocols in terms of image acquisition and objective analysis remain equivocal. By utilizing reflective cross-polarized light digital photography with a standardized white balance gray reference card serving as the known reference, in conjunction with a specific digital single-lens reflex (DSLR) camera profile and digital photographic processing software working in the CIE L*a*b* (1976) color space, one can achieve standardized image acquisition and subsequent objective image analysis. The goal of this systematic approach is to identify the most efficient and effective means to generate consistent and optimum visual integration and restorative outcomes through numerical quantification, in order to enable clinicians and technicians to work predictably even when they are in different geographic locations.

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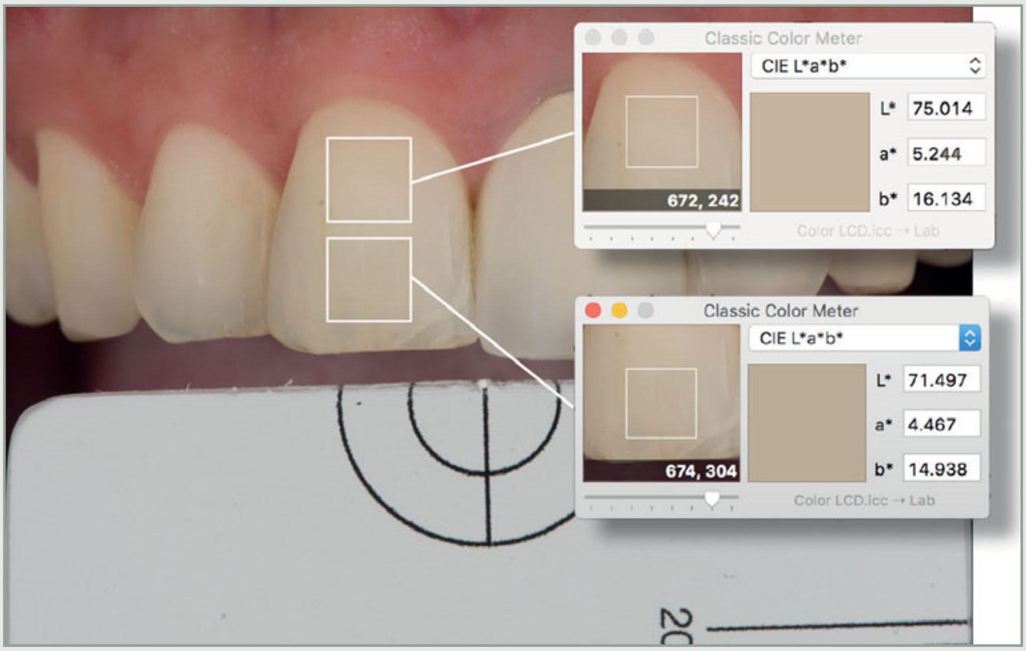


Classic Color Meter
CIE L*a*b*
672, 242
L* 75.014
a* 5.244
b* 16.134
Color LCD.icc → Lab

Classic Color Meter
CIE L*a*b*
674, 304
L* 71.497
a* 4.467
b* 14.938
Color LCD.icc → Lab

Introduction

It has been known for some time that shade selection in dental practice is an important but difficult task.[1-3] Tooth shades can be analyzed by two methods: visual and instrumental.[4] The most popular method for shade matching is the visual correlation method utilizing stock shade guides. The VITA classical shade guide (VITA Zahnfabrik) is the most widely used shade guide in dental practices and laboratories worldwide.[5]

Despite the availability on the dental market of many types of stock shade guides, matching shade tabs with natural teeth in the intraoral environment remains a formidable challenge.[6] This can be attributed to a number of circumstances, which include: operator ocular dependency;[7,8] incompatibility between shade guide and restorative material; inter-batch shade tab variation from the same manufacturer, showing variability in basic color parameters;[9] inadequate shade range distribution;[10,11] and lack of standardization of tooth shades among different ceramic manufacturers.[12,13] Instruments for clinical shade determination include spectrophotometers, colorimeters, and digital camera systems with corresponding software.[14,15] Computerized colorimeters and spectrophotometers for use in dentistry have been available for a number of years. They have proven to produce stable results but are not associated with higher accuracy.[16]

Fig 1 The digital PCM setup consists of a DSLR camera, a suitable macro lens, a macro flash, and a matching cross-polarization filter.

Digital imaging for use in color matching, which is continuously developing, is presently a topic of great interest. Digital cameras are user-friendly, relatively inexpensive, and readily available in most dental practices and laboratories. The color information obtained from digital images is relevant for use in the dental setting. For these reasons, digital cameras are considered to be a suitable and practical target device for the advancement of color matching in dentistry.[17] The aim of this article is to explore the possibilities of a novel approach to shade management (eLABor_aid) utilizing a digital photocolorimetric (PCM) method and subsequent shade formulation without the use of stock shade guides.

Hardware requirements

The digital PCM setup

This consists of a digital single-lens reflex (DSLR) camera, a suitable macro lens, a macro flash, and a matching cross-polarization filter (Fig 1). This setup is in accordance with the statistical evaluation of 336 participants (clinicians and dental technicians) who have attended 30 dental photography courses globally, given by the authors over a period of 3 years. The distribution in Figure 2 shows the most commonly used camera brands, as well as lens focal lengths and flash combinations.

Eliminating glare

A number of years ago, professionals in the medical specialties of ophthalmology[18,19] and dermatology[20-25] started to successfully utilize reflective cross-polarized light photography because this technique mitigates the majority of specular reflections (glare). This practice was slowly adopted over the years in the dental field with analog film photography;[26-29] however, it remained an obscure and underutilized technique. Recently, there has been a resurgence of interest in the digital photographic illumination technique variant,[30-37] which aims to increase the accuracy and objectivity of dental shade evaluation and laboratory communication via the use of specialized polarization filters (polar_eyes, Emulation). This digital technique enhances visualization of surface and subsurface enamel characteristics in an unobstructed manner via a nondestructive contrast mechanism. By eliminating the superficial value influence, a high contrast/hypersaturated chromatic shade estimation map is immediately obtained for objective measurement. With the ability to spatially previsualize the enamel/dentin histoanatomy,[38] stratification interpretation can be significantly improved for modern esthetic dental materials. This is, in a way, a more intuitive/instinctive/visceral approach.

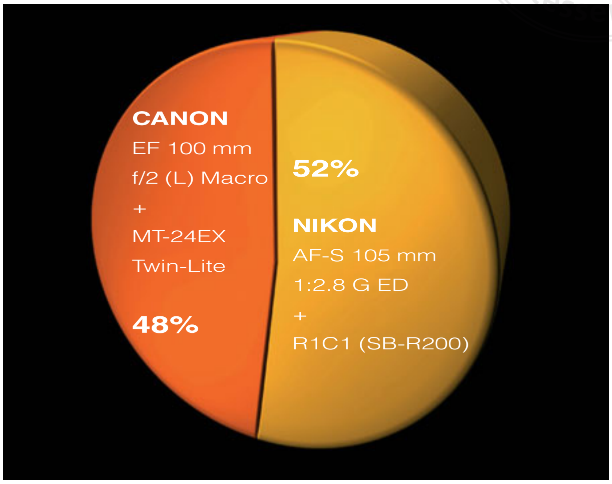


Fig 2 Pie chart showing the distribution of most commonly used DSLR camera brands, as well as focal lens lengths and flash combinations, gathered from 336 participants (clinicians and technicians) over a period of 3 years. The eLABor_aid system has been designed accordingly.

Image acquisition

In order to acquire digital images suitable for tooth shade quantification, standardization is necessary while using the

Table 1 Set distances that must be selected based on the camera lens/sensor-size pairing

DSLR sensor size	Lens focal length	Reproduction ratio	Object to focal plane distance
Full frame (FX)	60 mm	1:1.6	24 cm
Full frame (FX)	105 mm	1:1.6	37 cm
APS-C (DX)	60 mm	1:2.5	28 cm
APS-C (DX)	105 mm	1:2.5	45 cm

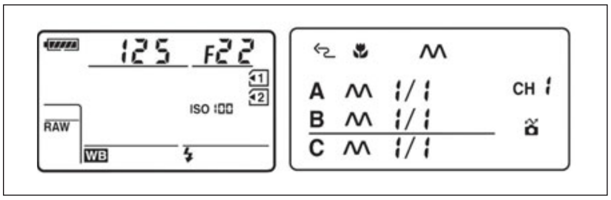


Fig 3 To mitigate the influence of ambient light and to ensure flash synchronization, the shutter speed should be set to 1/125 sec, with an aperture of f 22 for suitable DOF acquisition.

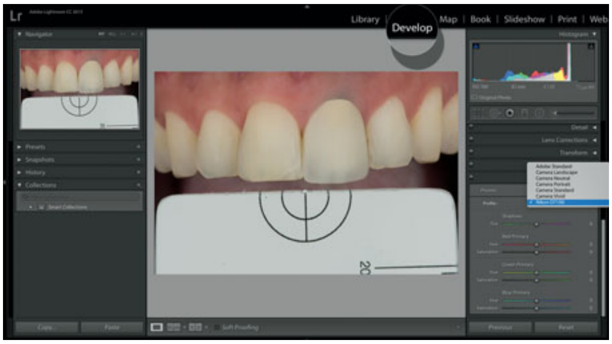


Fig 4 Before importing the clinical RAW file into Adobe Lightroom, it is first necessary to choose the correct DSLR camera profile from the camera calibration dropdown menu in the Develop mode.

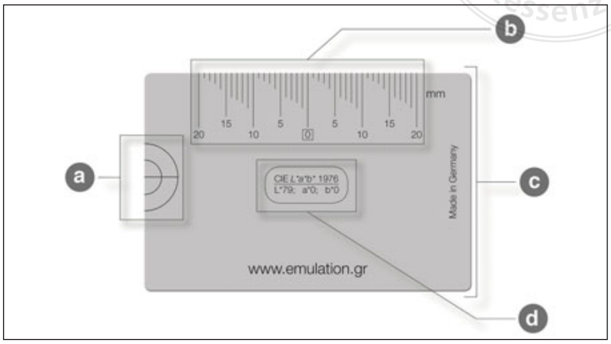


Fig 5 White balancing is usually carried out with the help of an achromatic object such as a gray reference card with the following features: a) Hairline cross reticle which assists with vertical alignment and distance calibration. The small circle should match with that of the viewfinder grid of most common APS-C sensor-type cameras, whereas the larger one should match with that of full-frame cameras. b) A millimeter scale for the assessment of proportions. c) The width of the card is equal to the average intercanine distance of Caucasian adults, to assist in cases where a particular DSLR model may not have any viewfinder grid at all. d) Defined color coordinates using the CIE L*a*b* system with low manufacturing tolerance (± 0.5).

camera in manual mode. A set distance should be selected based on the camera lens/sensor size pairing (Table 1). To mitigate the influence of ambient light and ensure flash synchronization, the shutter speed should be set to 1/125 sec, with an aperture of f 22 for suitable depth of field (DOF) acquisition (Fig 3). This aperture setting also avoids the detrimental issues related to diffraction (particularly in APS-C sensor), as further stopping down of the aperture serves only to decrease the image sharpness[39] and adds no additional benefit for shade estimation photography. The sensor sensitivity of 100 ISO should be selected, and image format should be set to RAW. The external ring or lateral flash should be set to maximum output (1/1) in manual mode. The use of TTL metering is not advisable due to the inherit variations in exposure program algorithm metering calculations.

Digital workflow

Camera synchronization

Color information received from digital cameras is device-dependent, ie, the actual color information, usually presented in red-green-blue (RGB) color space, differs between different devices. Proper calibration and color adjustment among digital devices is required for accurate color management.[40] Previous studies have performed spectral sensitivity characterization of digital cameras using a monochromator and a radiance meter to determine the relationship between the camera spectral sensitivity and the device-independent CIE color-matching functions using polynomial modeling and matrix multiplications.[41,42] A color target-based approach (ColorChecker Passport, X-Rite) offers a practical method for carrying out such camera profiling.[43] A total of 58 specific DSLR camera profiles were thus created using the PCM relevant for a dental setting. Before importing the clinical RAW file into Adobe Lightroom, it is necessary to choose the correct DSLR camera profile from the camera calibration dropdown menu in the Develop mode (Fig 4).

White balance

The data from the image sensor of a modern DSLR camera is typically modeled as being naturally linear. The white balance and color correction are often, though not always, linear operations, ie, the white-balanced/color corrected RGB data vector at each pixel location can be seen as a linear combination (via matrix multiplication) of the raw RGB vector at the same pixel. This is usually carried out with the help of an achromatic object such as a gray reference card[44] (white_balance, Emulation), which serves as the common denominator (Fig 5) by selecting the White Balance selector tool (pipette) and clicking on any of the four gray segments in the image[45] (Fig 6).

Brightness correction/exposure balance

Small variations in image brightness typically have their origin in inconsistent luminous flux output from the electronic flash as the batteries discharge. Brightness correction (ie, exposure balance)

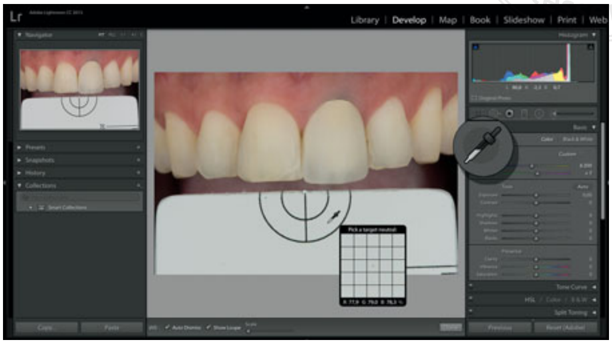


Fig 6 Selecting the White Balance selector tool (pipette) and clicking on any of the four gray segments in the image allows the user to carry out white balance correction.

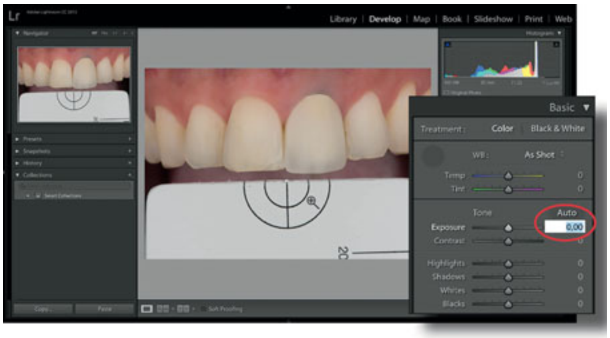
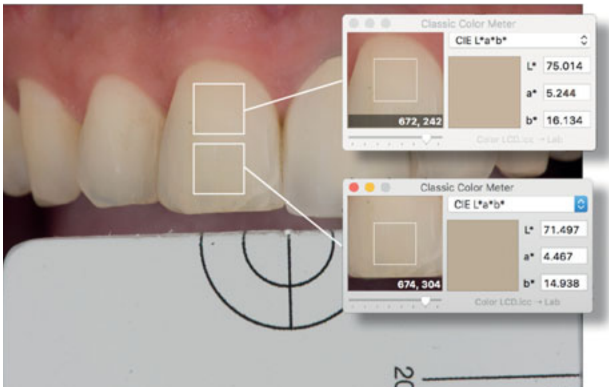


Fig 7 To carry out exposure balance, activate this function by clicking on the three zeros next to the Exposure slider. The cursor becomes a magnifying glass when moved over any of the four gray segments.

Fig 8 Measured L*a*b* values are displayed below the histogram when the magnifying glass (cursor) is held steadily in position. Operating the up or down arrow keys on the keyboard adjusts image exposure. This is carried out until the known luminosity value (L*79) of the gray reference card has been replicated (ie, -0,12).

is therefore necessary. It is carried out by adjusting the image exposure until the measured luminosity of the gray card matches that of the known luminosity L*79 (Figs 7 and 8).[46,47]



L* 75.014
a* 5.244
b* 16.134

L* 71.497
a* 4.467
b* 14.938

Fig 9 To obtain target tooth color coordinates in CIE L*a*b* color space, Classic Color Meter software is used. Measurement aperture size can easily be adjusted to quantify the average target tooth color in the area of interest, usually the cervical and middle third.

Measuring target tooth shade

In order to obtain target tooth color coordinates in CIE L*a*b* color space, Classic Color Meter software (https://www.ricciadams.com/projects/classic-color-meter) is used. Measurement aperture size can be easily adjusted to quantify the average target tooth color in the area of interest, usually the cervical third (Fig 9).

Creating a statistical model

CIE L*a*b* color coordinates are usually referred to as colorimetric data, as opposed to spectral data obtained with a spectrophotometer. As such, colorimetric data is relative rather than absolute, ie, the actual CIE L*a*b* values of an object are dependent on the measurement device and illumination geometry used. Existing tooth color coordinates from the literature can therefore not be used. Instead, the CIE L*a*b* color coordinates

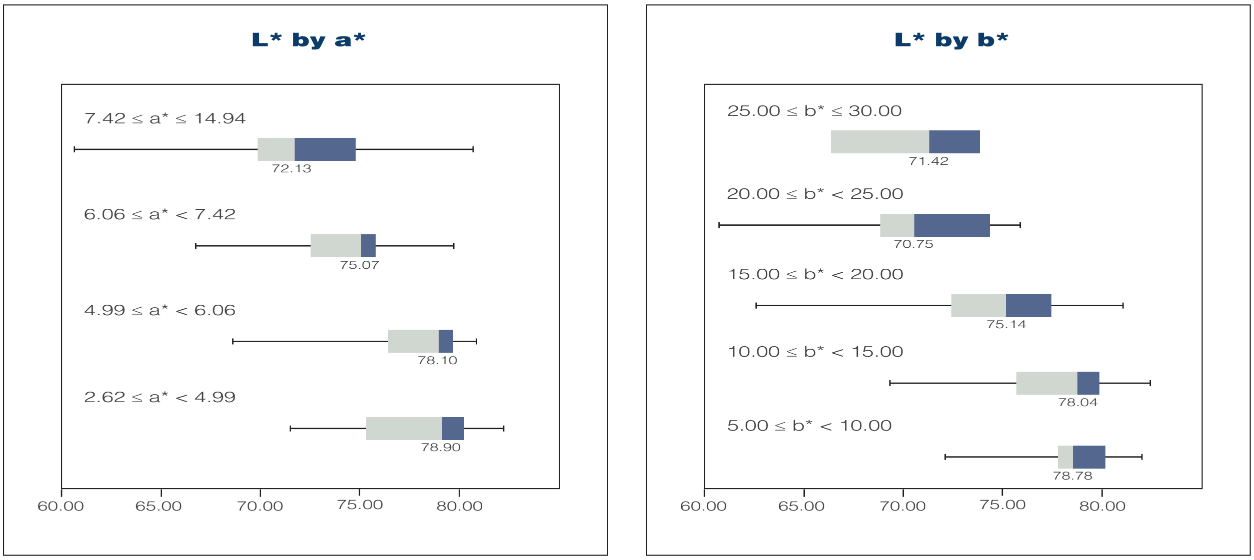
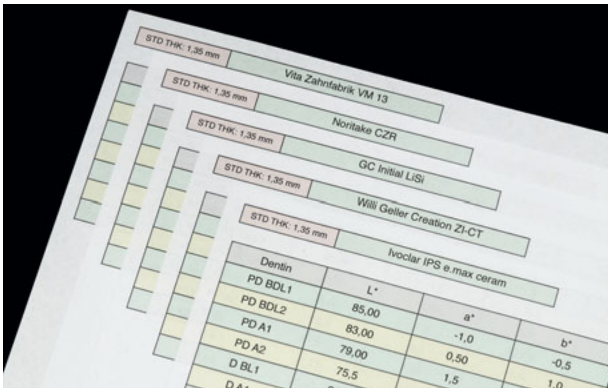


Fig 10 CIE L*a*b* color coordinates of 147 intact unrestored maxillary central incisors of a Caucasian population were acquired *in vivo* using the same PCM in order to obtain a basic statistical model. A qualitative analysis was used to create a mixing system.



STD THK: 1,35 mm — Vita Zahnfabrik VM 13

STD THK: 1,35 mm — Noritake CZR

STD THK: 1,35 mm — GC Initial LiSi

STD THK: 1,35 mm — Willi Geller Creation ZI-CT

STD THK: 1,35 mm — Ivoclar IPS e.max ceram

Dentin	L*	a*	b*
PD BDL1	85,00	-1,0	-0,5
PD BDL2	83,00	0,50	1,0
PD A1	79,00	1,5	
PD A2	75,5		
D BL1			

Fig 11 Interpolation charts based on the CIE L*a*b* color coordinates of the most common ceramic systems were created, assuming standard values for veneering thickness. The charts allow for the identification of the closest dentin color of the respective ceramic system, and offer mixing ratios to increase a* and b* individually, as well as to lower luminosity, if needed.

Fig 12 After the closest dentin color of the respective ceramic system has been determined, a set of ceramic stains is used to adjust the chroma and luminosity. While two stains – E22 (basic yellow) and E21 (basic red) – serve to increase chroma, a brown stain (E10) can be used to lower the luminosity without affecting the chroma.

of 147 intact unrestored maxillary central incisors of a Caucasian population were acquired *in vivo* using the same PCM so as to establish a statistical model. A Kolmogorov-Smirnov test showed a normal distribution of a* ($P = 0.169$), and b* ($P > 0.200$), but not L* ($P = 0.001$). A qualitative analysis was used to create a simple mixing system (Fig 10).

Shade formulation

In order to transfer the target tooth color into an individual dentin ceramic mixture in a practical way, the statistical model was used to create interpolation charts based on the CIE L*a*b* color coordinates of the most common ceramic systems, assuming standard values for veneering thickness (1.35 mm) and background color (Fig 11). The chart allows for the identification of the closest dentin color of the respective ceramic system, and offers mixing ratios to increase a* and b* individually and to lower luminosity, if needed, using a set of ceramic and stain portioners. Three IPS Ivocolor Essence (Ivoclar Vivadent) stains are used for this purpose: E21 (basic red), E22 (basic yellow), and E10 (mahogany). While the first two stains (E21 and E22) serve to increase the chroma, the third stain (E10) is used to lower the luminosity[48] (Fig 12). Stains from other manufacturers may also be suitable, providing they satisfy the scalability requirement of the linear mixing law for colored materials (Beer–Lambert law).[49]

Previsualization

The aforementioned mixing ratios rely on standard values for veneering thickness and background color. In clinical reality, however, the precise amount of available veneering space is subject to variations. The same is true for back-

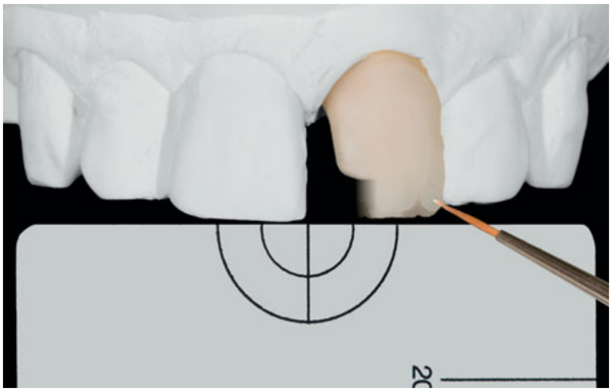


Fig 13 In order to verify the accuracy of the dentin mixture, considering variations in available veneering thickness and background color, a nontoxic high-refractive index liquid can be used to achieve previsualization of the color of the unsintered ceramic, which can subsequently be measured on the actual framework and master model.

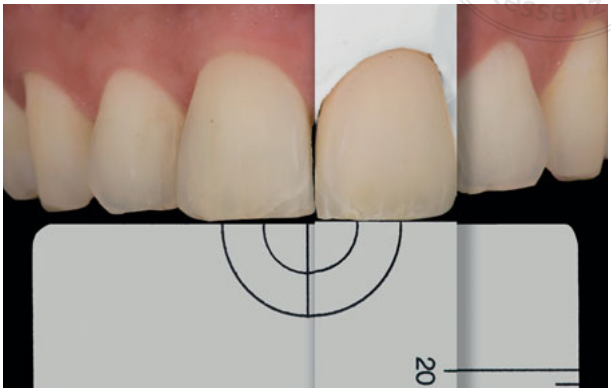


Fig 14 Incisal characteristics and other details can be checked via visual and numerical comparison using the digital try-in. For this purpose, the digital image of the restoration on the master model can be superimposed onto the clinical image obtained from the dental surgery using either Adobe Photoshop or Apple Keynote software.

ground colors. While small variations in veneering thickness of ± 0.25 mm do not show significant color changes, larger variations affect both the luminosity and chroma. One and the same dentin mixture may show higher luminosity and lower chroma if less veneering space is available, and the opposite is true if the veneering space exceeds 1.5 mm. In order to verify the accuracy of the dentin mixture, considering such individual circumstances, and to adjust the luminosity and chroma, if necessary, a nontoxic high-refractive index liquid (visual_eyes, Emulation) can be used to achieve previsualization of the color of the unsintered ceramic,[50-53] which can subsequently be measured on the actual framework and master model (Fig 13).

Figs 15 and 16 Polarized and reflected image of final metal ceramic restoration placed *in situ* showing good agreement between digital try-in and clinical outcome.

Digital try-in

While the primary purpose of the eLABor_aid protocol is to replace stock

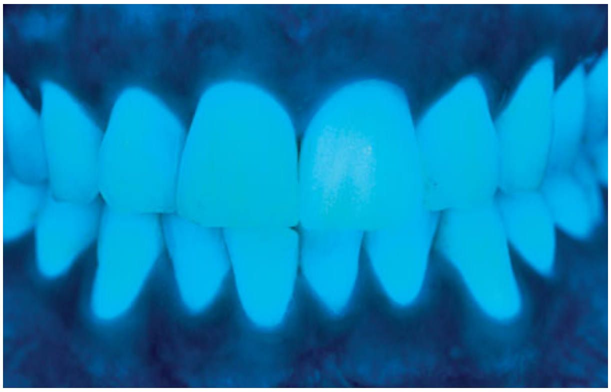


Fig 17 Fluorescence is a relevant optical property of natural teeth and should be emulated faithfully to avoid metameric failure in UV-rich environments. Modern dental ceramics possess adequate fluorescence, with similar excitation and emission peaks to those of natural dentition. Brighter shades usually correspond with higher fluorescence emission, whereas the opposite is true for darker shades.

Fig 18 The final outcome as it would be perceived in a normal, everyday setting. As with all other cases presented in this article, color matching was carried out over a geographical distance, with no direct interaction between the patient and dental ceramist.

shade guides to determine the correct dentin shade, the credible imitation of more intricate details such as incisal characteristics can be checked via visual and numerical comparison using the digital try-in. For this purpose, the digital image of the restoration on the master model can be superimposed onto the clinical image obtained from the dental surgery, using either Adobe Photoshop or Apple Keynote software (Fig 14), showing good agreement with the clinical try-in (Figs 15 to 18).

Clinical applications

Over a period of 2 years of practical implementation of the eLABor_aid system, the authors and other members of the dental restorative community have observed a number of encouraging results. While the initial indication was limited to traditional fixed dental prostheses work using either metal ceramic or ZrO2 restorations, the approach seems to also show potential for more translucent restorations such as lithium disilicate or even feldspathic veneers. Figures 19 to 30 show a number of clinical cases that were solved using the eLABor_aid system, bridging large geographic distances where direct interaction for the purpose of shade evaluation between the patient and the dental technician was not possible.

Discussion

One must strive to innovate new and improved processes that can provide better quality at lower costs. The path that was chosen by the authors was to fabricate pertinent complimentary components (polar_eyes, white_balance, visual_eyes) around the core DSLR imaging technology that is readily available in the majority of dental practices and laboratories and which has been

Figs 19 to 22 Second clinical case showing completed metal ceramic restoration *in situ*, documented in a variety of light conditions.

Figs 23 to 26 Third clinical case showing placed metal ceramic restoration *in situ*. The presence of discolorations of the substrate always presents a challenge due to the influence on perceived periodontal color. In such esthetically sensitive cases, optimal shade management provides a substantial contribution for achieving the best possible compromise, as is often required in clinical reality.

Figs 27 to 30 Fourth clinical case demonstrating the potential of the eLABor_aid system for application with all ceramic restorations.

deemed suitable for shade quantification[54-64] (Table 2).

The eLABor_aid protocol (Fig 31) allows for objective shade communication and accurate color matching over distances and without the need for stock shade guides or personal consultation between the patient and the dental technician. Standardization in dental photography for shade selection can help to maximize compatibility, interoperability, and repeatability. The goal of this systematic approach is to identify the most economic, efficient, and effective means to generate consistent and optimum visual integration restorative outcomes through numerical quantification, minimizing the threshold to a target value $\Delta E < 1$. This workflow equips the dental ceramist with powerful analytical tools such as the CIE L*a*b* color system, extending beyond the limitations of the Vita Classical system, and providing the ability to create custom dentin mixtures, in order to quantify objectively and perform digital try-ins beforehand for optical integration verification. Additionally, the workflow enables the technician to scrutinize, at any given stage, the direction of the shade-matching outcome during the buildup, allowing increased predictability and overall control.

Although the eLABor_aid protocol provides a robust workflow, light propagation in natural teeth remains highly complex and dynamic in nature,[65] in stark contrast with current restorative materials, which remain relatively simplistic and relatively static in the way they interact with light.

Merely conditional color matching between natural dentition and artificial indirect restorations is possible.[66] Hence, projected and actually measured color

Table 2 Previous works by other authors have often indicated that digital cameras may be a suitable choice for the quantification of tooth color

Author	Year of publication	Study design	Methodology	Results
Dhruv et al[63]	2016	*In vitro*	Digital imaging vs spectrophotometer	It can be concluded that an DSLR camera with Adobe Photoshop CS5.1 as an adjunct can be used as an alternative to spectrophotometer
Bhandari et al[61]	2014	*In vivo*	Digital imaging vs spectrophotometer	There was no statistically significant difference found between digital cameras and spectrophotometers, which shows that digital cameras and spectrophotometers are equally reliable
Carney and Jonston[62]	2016	*In vitro*	Digital imaging vs spectroradiometer	This regression renders the color information from a digital image clinically relevant for a wide range of tooth color shades that can be used to accurately translate color information for color matching purposes in restorative and prosthodontic dentistry
Elter et al[55]	2005	*In vitro*	Digital imaging vs spectroradiometer vs visual assessment	It appears that the resolution capacity of a digital camera can increase the reliability of color selection
Jarrad et al[54]	2005	*In vitro*	Digital imaging vs visual assessment	The digital camera can be used as a means of color measurements in the dental clinic
Lakhanpal and Neelima[64]	2016	*In vitro*	Digital imaging vs spectrophotometer	The difference in the mean L*a*b* values between spectrophotometer and polarization dental imaging modality (PDIM) was insignificant
Oh et al[58]	2010	*In vivo*	Digital imaging vs visual assessment	The digital PCM method is valid for the range of human teeth based on the Vitapan Classical shade guide
Peskersoy et al[60]	2014	*In vitro*	Digital imaging vs spectroradiometer	Both software and spectrophotometric analyses have advantages such as evaluating the results objectively and numerically; also, treatment outcomes could be preserved
Schropp[57]	2009	*In vitro*	Digital imaging vs visual assessment	Shade matching assisted by digital photographs and computer software was significantly more reliable than by conventional visual methods
Wee et al[56]	2006	*In vitro*	Digital imaging vs spectroradiometer	Commercial SLR digital cameras when combined with the appropriate calibration protocols showed potential for use in the color replication process of clinical dentistry
Yamanel et al[59]	2010	*In vitro*	Digital imaging vs colorimeter	Digital imaging method could be used in the assessment of color parameters

difference values (ΔE*) are only applicable under directional illumination using D65 (daylight). Detrimental metameric effects can be most noticeably observed when illuminants change,[12] whereas changing viewing angles typically results in small differences of perceived brightness.

Another overall limiting factor is that the majority of available dental ceramic systems are still based on the Vita Classic system. Furthermore, the restorative team may occasionally encounter another substantial obstacle, which is that, according to the aforementioned statistical analysis, nearly 35% (34.93%) of natural teeth have an average CIE L*a*b* color distribution of L*79.19 (min L*77.00; max L*81.62); a*5.03 (min a*2.62; max a*8.35); b*12.24 (min b*6.14; max b*18.79), which exceeds both the luminosity and chroma of Vita Classical shade B1 (L*74.7; a*1.3; b*10.4). In such cases, it may be prudent to reproduce the target tooth color utilizing the brightest bleach dentin provided in a given ceramic system as a starting point for shade formulation, which subsequently can lead to a successful match in the majority of cases.

More high-quality research is needed to verify the effectiveness and reliability of the eLABor_aid system in a controlled clinical trial.

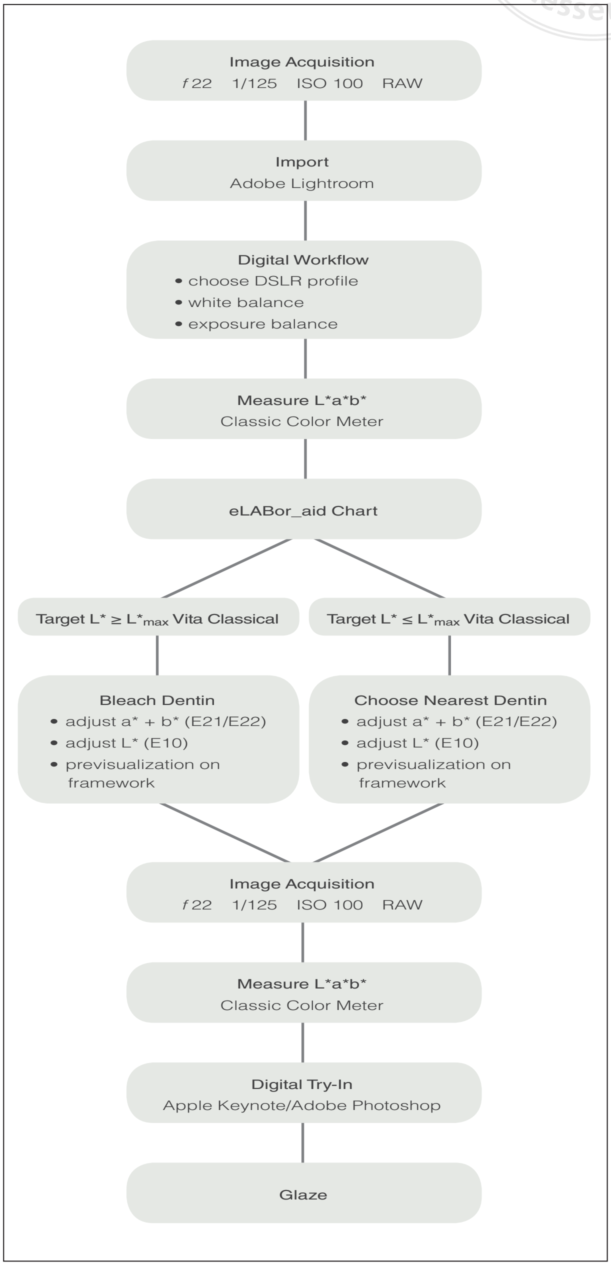


Fig 31 Flowchart demonstrating the various steps of the eLABor_aid protocol.

Acknowledgment

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