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CLINICAL ARTICLE

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Objective shade matching, communication, and reproduction by combining dental photography and numeric shade quantification

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[Corrections added on Oct 9, 2020 after first online publication: In the initial publication, the legends of figures 10–16 were not set with the correct figures. They have been amended.]

Abstract

Objective: The subject of this case report is the application of a newly developed workflow for objective shade communication sans visual shade assessment or the use of shade guides.

Clinical Considerations: Clinical complications stemming from issues relating to esthetic integration can present a burden on the restorative team, often resulting in strenuous relationships among its members. The faithful imitation of the optical appearance of dental hard tissues with direct- and indirect restorations has been at the center of interest in a great number of publications from the realm of esthetic dentistry over the past 40 years. The present report describes a new approach to objective shade communication, by transcending the role of dental photography from its purely descriptive purpose to the level of quantification, thus abandoning the use of the established shading regimes and replacing them with a patient personal shade recipe based on the CIELAB color space instead.

Conclusions: Objective shade communication is possible with the eLAB system by combining numeric shade quantification with dental photography.

Clinical Significance: The eLAB system presents a viable alternative to the traditional approach to shade communication and shade matching in dentistry.

KEYWORDS

dental ceramics, dental photography, shade communication, shade matching

1 | INTRODUCTION

Reliable shade matching of indirect restorations with natural dentition remains to be a formidable challenge, even for the most experienced restorative team. Redo's are unfortunately common[1] and costly,[2] providing frequent cause for friction among its members. The precise circumstances leading to shade mismatches are complex and easily underestimated. The actual process of shade matching can be distilled down to two main procedural elements, each harboring its own specific pitfalls.

- Shade selection and communication
- Shade matching using available materials and techniques

1.1 | Shade selection and communication

In daily practice, shade selection and shade communication is still largely carried out with the use of shade guides in combination with visual shade assessment.[3] The well-known pitfalls of this approach include the inadequate range of available shades, their illogical distribution as well as inconsistencies among different clinicians using shade guides for visual shade assessment.[4] Although improvements have been attempted with the introduction of newer and more advanced shade guide systems, most notably the Vita 3D Master shade guide (Vita Zahnfabrik, Bad Säckingen, Germany), widespread adoption in dentistry has been limited.[5] Moreover, there does not appear to be a uniform standard for tooth colors in dentistry, leading to inconsistent shading regimes among different manufacturers for materials intended for direct[6-8] as well as for indirect use.[8-12]

1.2 | Shade matching using available materials and techniques

The actual process of shade matching is largely empirical and highly dependent on the dental ceramist's level of skill and experience. Often unbeknown to many ceramists, multiple variations of only two essential layering techniques are in common use, namely that of Yamamoto[13] and that of Geller.[14] The precise selection process from a large range of individually shaded ceramic powders is usually based on the evaluation of images, custom drawings of shade maps and above all, personal preference and experience.[15] The complexity of this process usually imposes a considerable level of uncertainty regarding the predictability of shade matching in clinical reality.[16] The following section describe a clinical report and illustrates how a standardized protocol for dental photography and colorimetry can help to overcome some of the aforementioned problems.

2 | CLINICAL REPORT

A 35-year-old male patient presented in a private dental office in Zagreb, Croatia, complaining about the color of his maxillary left central incisor. The clinician opted for full crown preparation to accommodate an all-ceramic restoration.

2.1 | Theoretical background

2.1.1 | Using a color space instead of shades tabs

The Commission Internationale de l'Éclairage (CIE) adopted a new color space in 1976 with the official terminology CIE (1976) $L^*a^*b^*$, simply abbreviated as CIELAB. The realization that equal chromaticity differences of colors of varying lightness would not yield equal visual differences, led to the desire for a more perceptually uniform color space than the previous tristimulus or chromaticity color spaces.[17] The CIELAB color space is an opponent-type system where the variables L^*, a^*, and b^* represent lightness, redness-greenness and yellow-blueness, respectively.[18] The main aim of the development of the CIELAB color space, however, was to provide a uniform practice for the quantification of color differences, which cannot be easily done with the aforementioned color spaces.[19] This feature makes it suitable for dental research. A Pubmed search using the keywords "CIELAB" and "Dentistry" returned 384 results over the last 20 years that include both words, demonstrating the popularity of CIELAB among dental researchers. Due to its objectiveness, logic and the ability to express color differences numerically, CIELAB forms the foundation for the eLAB system thus replacing the use of stock shade guides.

2.1.2 | Expressing color difference relative to clinical context

It is acknowledged that although CIELAB is approximately visual uniform, it is not in fact a totally visual uniform color space. Gradual improvement of color difference equations resulted in CIEDE2000 (abbreviated ΔE_{00}), a color difference formula that can more reliably predict perceived color differences. Note, however, that the CIEDE2000 equation is still based on CIELAB color space. The definition of numerical thresholds for visual perception is dependent on the exact industry and application. They may differ somewhat between them.[20] Paravina et al[21] have determined a ranking scale which relates measured ΔE_{00} color differences to clinical relevance and this approach has been adopted by the eLAB system.

2.2 | Practical steps and considerations

2.2.1 | Photographic protocol

The eLAB system is centered around a standardized protocol for dental photography. Disciplined adherence to its guidelines and sequences is essential for ensuring accurate and repeatable results.

2.2.2 | Dehydration

The opacity of enamel increases due to dehydration, making teeth appear whiter than during their normal state of hydration.[22] This effect provides the most common cause for complication during esthetic integration. Relatively few studies are available which have examined the effects of dehydration on tooth color, and these have deployed various measurement regimes and equipment.[23-26] Both, Burki et al and Suliman et al reported color changes after 10 minutes of exposure to air that exceed the clinical 50/50 acceptability threshold (ΔE_{00} 3.84 (SD 0.16) vs ΔE_{00} 4.88 (SD 2.48)). Suliman et al also found a mean color difference of ΔE_{00} 3.94 (SD 2.62) after only 1 minute of exposure to air. However, when colorimetric results are obtained for the purpose of evaluation, it is essential to make sure that like is being compared to like. For the data under consideration, settings for the chosen illuminants, standard observers and illumination geometries must be the same, otherwise no meaningful comparison is possible and thus differences between results may merely demonstrate differences in measurements conditions.[27] For the eLAB protocol, standard advice has been issued to stay well below the 2 minutes dehydration threshold for measuring the target tooth color. This step is best carried out right at the beginning of the treatment.

2.2.3 | Use of cross polarization

The use of cross polarization presents a convenient method to record the appearance of teeth without specular surface reflections (gloss) to ensure accurate color measurement.[28] The most straightforward approach to achieving adequate cross polarization is with the use of a ring flash, paired with the appropriate cross polarization filter (Emulation, Freiburg, Germany) (Figure 1). The use of a lateral flash is also possible, but care must be taken to ensure correct alignment between the polarizers covering the flash which must be in a perfectly perpendicular orientation to the analyzer filter placed over the lens (Figure 2). The most important implication of the use of cross polarization is the extraction of a single beam of polarized light from a burst of unpolarized light and that the rest of the light is wasted.[29] To account for this effect, it is of paramount importance to switch off E-TTL and to use the manual mode instead, with flash intensity set to maximum (1:1) on all channels in order to prevent severely underexposed images (Figure 3).

2.2.4 | Use of white-balance card

The data from the image sensor of a modern DSLR camera is typically modeled as naturally being linear. The white balance and color correction are often, though not always, linear operations upon them. That is, 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. RGB values are then converted to CIELAB using the standard intermediate XYZ space. This process is automatically carried out by the eLAB_prime software (Emulation, Freiburg, Germany) using a dedicated grey reference card

FIGURE 1 The use of cross polarization presents a convenient method to record the appearance of teeth without their specular reflections (gloss) to ensure accurate color measurement. The most straightforward approach to achieving adequate cross polarization is with the use of a ring flash, paired with the appropriate cross polarization filter

FIGURE 3 For cross polarized photography it is of paramount importance to switch off E-TTL and to use the manual mode instead, with flash intensity set to maximum (1:1) on all channels in order to prevent severely underexposed images

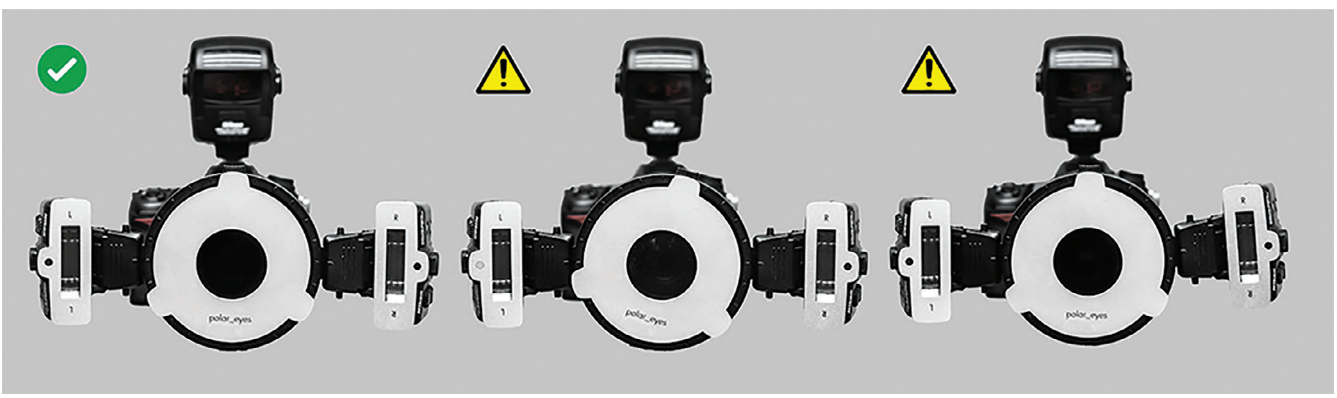

FIGURE 2 The use of a lateral flash is also possible if attention is paid to the correct alignment between the two polarizing filters covering the lens and the flash

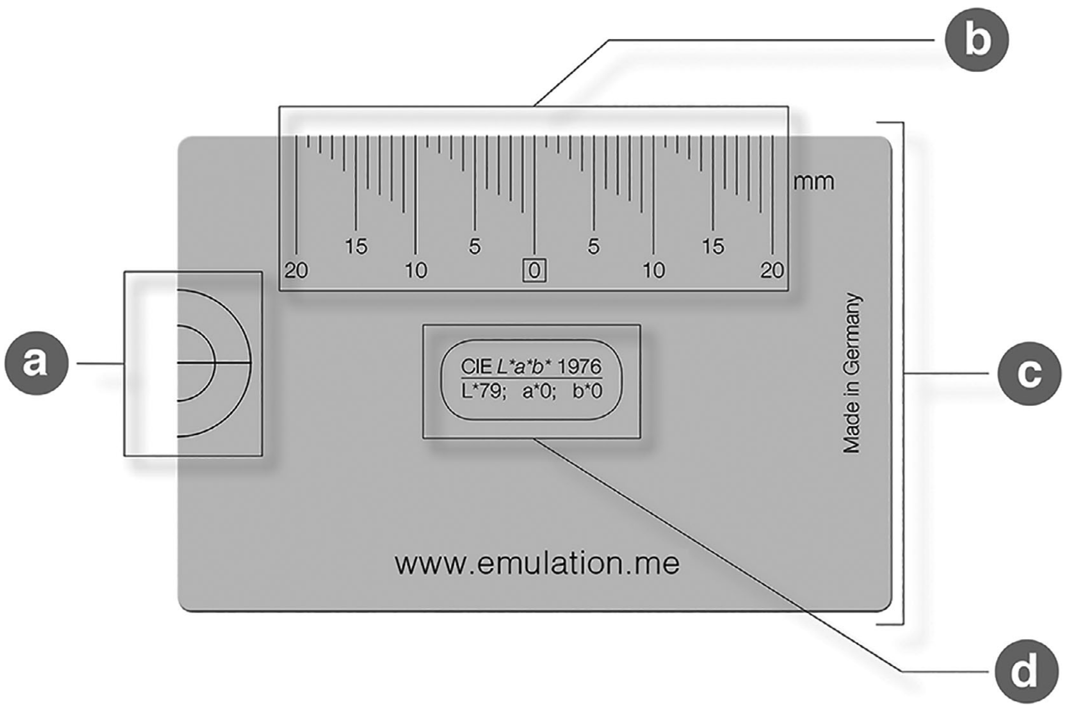

FIGURE 4 A dedicated grey reference card is used to mitigate the influence from cross polarization on color temperature and above all, to synchronize DSLR cameras of different models and manufacturers reliably. It is equipped with a hair cross style aiming circle to aid with correct positioning, A, a millimeter scale, B, and the width of the white_balance card corresponds to the average intercanine distance of the Caucasian adult to aid in finding the correct working distance, C. The known reflectance values are noted on the grey reference card for manual processing in proprietary software like Adobe Lightroom or Photoshop

(Emulation, Freiburg, Germany) and a fully linear RAW processing pipeline to mitigate the influence from cross polarization on color temperature and above all, to synchronize DSLR cameras of different models and manufacturers reliably (Figure 4).[30]

2.2.5 | Exposure and aperture settings

Photo colorimetric quantification with the eLAB system is sensitive to strict adherence to fixed parameters in order to provide a uniform guidance for the measurement of tooth color using CIELAB. This leaves little room for personal preference or interpretation. The correct camera settings for exposure time is 1/125 seconds and for the aperture *f*22 while image quality must be set to RAW at all times, regardless of the model and make of DSLR camera used (Figure 5). The associated software is capable of synchronizing over 100 different DSLR camera models with each other to a high degree of intercomparability (ΔE_{00} ~1.00) but only if the original RAW data (ie, Nikon Electronic Format (NEF) or Canon Raw (CR2)) is available. Compression formats like JPEG or proprietary formats like DNG (Adobe) are not supported.

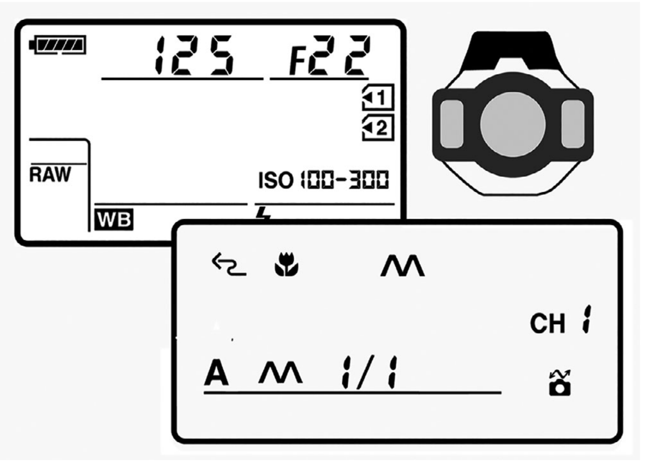

FIGURE 5 Photo colorimetric quantification with the eLAB system is sensitive to strict adherence to fixed parameters in order to provide a uniform guidance for the measurement of tooth color using CIELAB. The correct camera settings for exposure time is 1/125 seconds and for the aperture f22 while image quality must be set to RAW at all times, regardless of the model and make of DSLR camera used

2.2.6 | Finding the correct ISO prior to first use

The only variable which requires individual definition is the correct value for the ISO. This is best determined prior to clinical implication of the eLAB system, through a simple exposure series starting with an ISO value of 100 and incremental increase toward a maximum value of ISO 400. The resulting RAW images are then batch-imported into the eLAB_prime software to determine which ISO value yields the

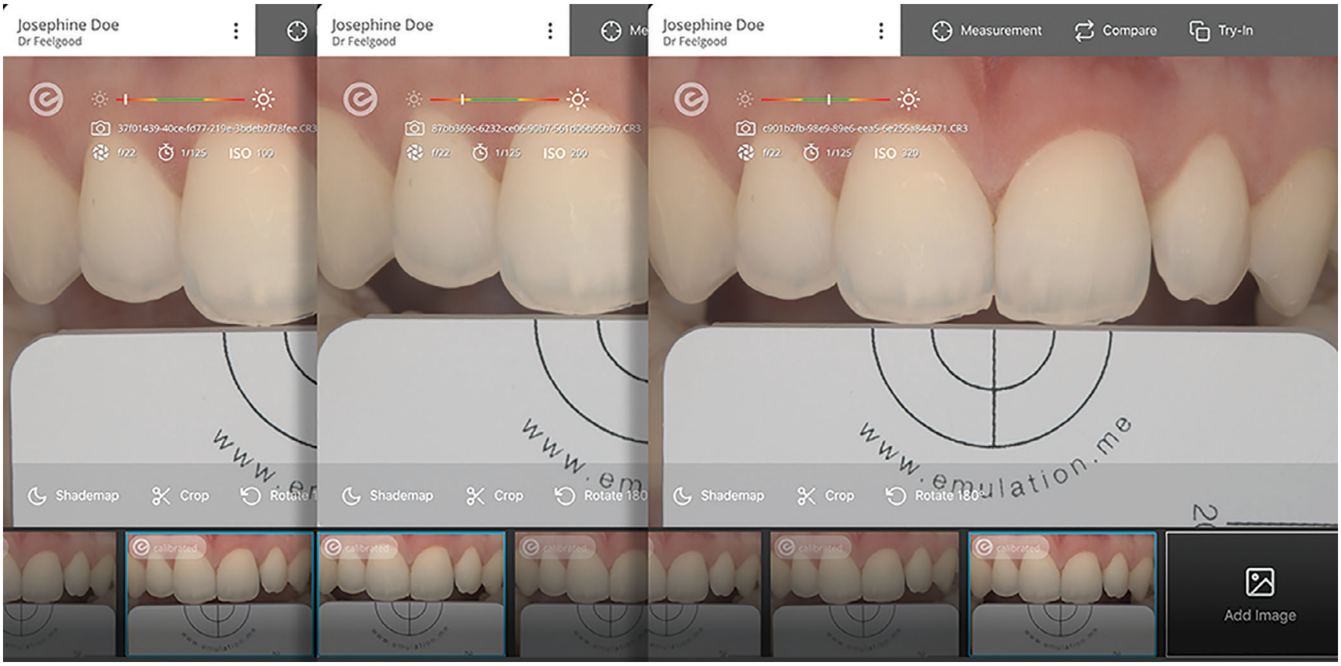

FIGURE 6 Prior to first use and for initial set-up it is necessary to find the correct ISO value for the chosen combination of DSLR camera, lens and type of flash. This is best determined through a simple exposure series starting with an ISO value of 100 and incremental increase toward a maximum value of ISO 400. The resulting RAW images are then batch-imported into the eLAB_prime software to determine which ISO value yields the ideal exposure by referencing the exposure indicator in the top left corner of each image. A warning triangle indicates the use of incorrect settings or when severe under- or over exposure has been detected

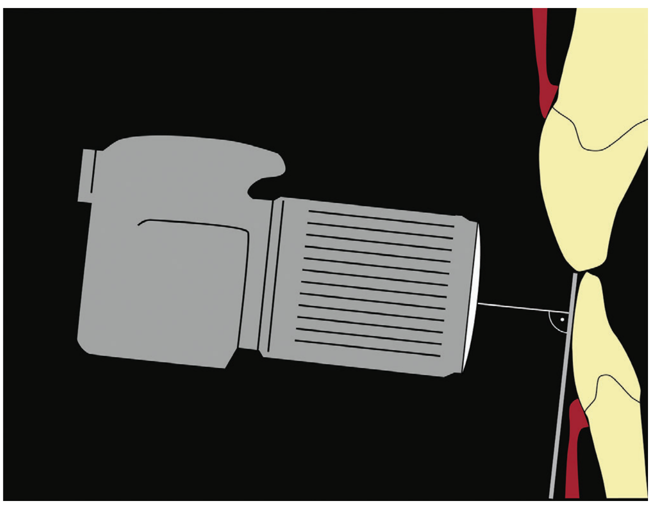

FIGURE 7 During image acquisition the optical axis should be normal to the vertical plane of the white_balance card which in turn should be positioned just below the incisal edges of the maxillary centrals and roughly parallel to the labial plane of the maxillary anteriors

ideal exposure for the given combination of DSLR body, macro lens and type of flash. This is easily done by referencing the exposure indicator in the top left corner of each image. A warning triangle indicates the use of incorrect settings or when severe under- or over exposure has been detected (Figure 6).

2.2.7 | Shooting position and distance

During image acquisition the optical axis should be normal to the vertical plane of the white-balance card which in turn should be positioned just below the incisal edges of the maxillary centrals and roughly parallel to the labial plane of the maxillary anteriors (Figure 7). It is a common error to choose a too remote working distance. The shooting distance should roughly equal a canine-to-canine reproduction ratio. Table 1 shows the ideal reproduction ratios and working distances for Canon and Nikon DSLR cameras with either full frame or APS-C type sensors and for the most common macro lenses used for dental photography. When using the view finder, care should be taken that the white-balance card runs through the middle of the frame, covering the entire lower half, while the upper half is reserved for the teeth to be quantified (Figure 8).

2.2.8 | Digital work-flow

Once the cross polarized image has been taken in accordance with the photographic protocol, it can be imported into the eLAB_prime application for convenient automatic calibration. The desired target shade is obtained through image analysis using artificial intelligence algorithms to determine the distribution of the most common tooth color with the help of statistical modeling. This process is carried out for two areas of the target tooth, the middle and lower third as well as for the incisal third (Figure 9). The same process is applied when it is

TABLE 1 Ideal reproduction ratios and working distances for Canon and Nikon DSLR cameras with either full frame or APS-C type sensors and for the most common macro lenses used for dental photography

Lens type	Sensor type	Reproduction ratio	Working distance (cm)
Canon EF 100 mm f/2.8 L IS USM Macro	Full Frame	1:1.5	19
Canon EF 100 mm f/2.8 L IS USM Macro	APS-C	1:2	21
Canon EF 100 mm f/2.8 USM Macro	Full Frame	1:1.5	21
Canon EF 100 mm f/2.8 USM Macro	APS-C	1:2	23
Canon EF-S 60 mm f/2.8 Macro USM	Full Frame	1:1.5	12
Canon EF-S 60 mm f/2.8 Macro USM	APS-C	1:2	14
Canon EF 50 mm f/2.5 Macro	Full Frame	1:1.5	17
Canon EF 50 mm f/2.5 Macro	APS-C	1:2	20
Sigma 105 mm f/2.8 EX DG OS HSM Macro	Full Frame	1:1.5	20
Sigma 105 mm f/2.8 EX DG OS HSM Macro	APS-C	1:2	22
Sigma 105 mm f/2.8 EX DG Macro	Full Frame	1:1.5	24
Sigma 105 mm f/2.8 EX DG Macro	APS-C	1:2	27
Sigma 70 mm f/2.8 DG Macro Art Lens	Full Frame	1:1.5	15
Sigma 70 mm f/2.8 DG Macro Art Lens	APS-C	1:2	17
Tamron 90 mm f/2.8 Di Macro Lens	Full Frame	1:1.5	21
Tamron 90 mm f/2.8 Di Macro Lens	APS-C	1:2	23
Tamron 90 mm f/2.8 Di VC USD Macro Lens	Full Frame	1:1.5	20
Tamron 90 mm f/2.8 Di VC USD Macro Lens	APS-C	1:2	22
Tamron 90 mm f/2.8 Di VC USD Macro F017	Full Frame	1:1.5	19
Tamron 90 mm f/2.8 Di VC USD Macro F017	APS-C	1:2	22
Tokina 100 mm f/2.8 AT-X Pro Macro	Full Frame	1:1.5	22
Tokina 100 mm f/2.8 AT-X Pro Macro	APS-C	1:2	25
Nikon 60 mm f/2.8D AF Micro Lens	Full Frame	1:1.4	13
Nikon 60 mm f/2.8D AF Micro Lens	APS-C	1:2	16
Nikon 60 mm f/2.8G AF-S Micro Lens	Full Frame	1:1.4	23
Nikon 60 mm f/2.8G AF-S Micro Lens	APS-C	1:2	27
Nikon 85 mm f/3.5G AF-S DX VR Micro	Full Frame	1:1.4	17
Nikon 85 mm f/3.5G AF-S DX VR Micro	APS-C	1:2	20
Nikon 105 mm f/2.8G AF-S VR Micro	Full Frame	1:1.4	19
Nikon 105 mm f/2.8G AF-S VR Micro	APS-C	1:2	22
Sigma 105 mm f/2.8 EX DG OS HSM Macro	Full Frame	1:1.5	19
Sigma 105 mm f/2.8 EX DG OS HSM Macro	APS-C	1:2	22
Sigma 105 mm f/2.8 EX DG Macro	Full Frame	1:1.5	23
Sigma 105 mm f/2.8 EX DG Macro	APS-C	1:2	26
Sigma 70 mm f/2.8 DG Macro Art Lens	Full Frame	1:1.5	15
Sigma 70 mm f/2.8 DG Macro Art Lens	APS-C	1:2	17
Tamron 90 mm f/2.8 Di Macro Lens	Full Frame	1:1.5	20
Tamron 90 mm f/2.8 Di Macro Lens	APS-C	1:2	23
Tamron 90 mm f/2.8 Di VC USD Macro Lens	Full Frame	1:1.5	19
Tamron 90 mm f/2.8 Di VC USD Macro Lens	APS-C	1:2	22
Tamron 90 mm f/2.8 Di VC USD Macro F017	Full Frame	1:1.5	19
Tamron 90 mm f/2.8 Di VC USD Macro F017	APS-C	1:2	21
Tokina 100 mm f/2.8 AT-X Pro Macro	Full Frame	1:1.5	22
Tokina 100 mm f/2.8 AT-X Pro Macro	APS-C	1:2	25

desired to quantify the actual substrate color instead of selecting one of 8 Natural Die Material shades (Ivoclar Vivadent, Amherst, New York).

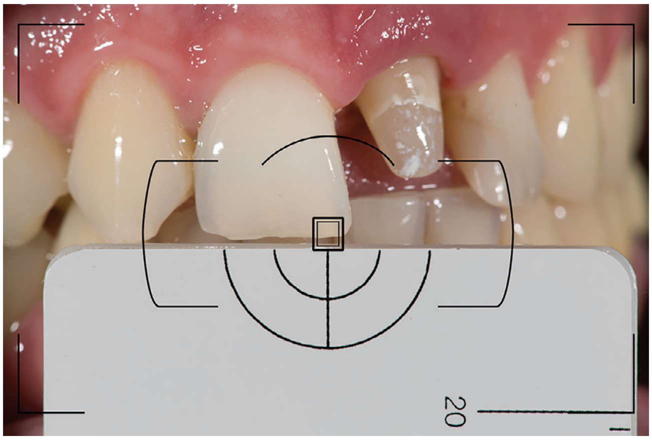

FIGURE 8 The shooting distance should roughly equal a canine-to-canine reproduction ratio. Using the view finder, care should be taken that the white_balance card runs through the middle of the frame, covering the entire lower half, while the upper half is reserved for the teeth to be quantified

2.2.9 | Obtaining a patient personal mixing recipe

The main strength of the eLAB system lies in its ability to provide individual shade matching recipes defined by the chromatic coordinates from an RGB image and under consideration of the substrate color as well as the amount of available space. This unique approach presents a departure from traditional shading regimes and also from its constraints and limitations. A photometrically acquired database of only few standard-shaded dentin powders (ie, Bleach 1, A1, A2, A3, D2) for each supported ceramic system provides the foundation for trichromatic subtractive color mixing. Three types of ceramic stains are used for this process; E21 (basic red), E22 (basic yellow), and E17 (anthracite/grey) (Ivoclar Vivadent) which can be mixed into any ceramic system regardless of its vitrification temperature or coefficient of thermal expansion (CET). A set of high precision instruments is available (Emulation, Freiburg, Germany) to accurately portion the quantities of stain (Figure 10). In relation to the fixed quantity of 0.60 g of dentin ceramic, which is adequate for one layered crown, the total amount of needed stain in 95% of all cases is 1.95% (16.78 mg; CI ±0.46 mg).

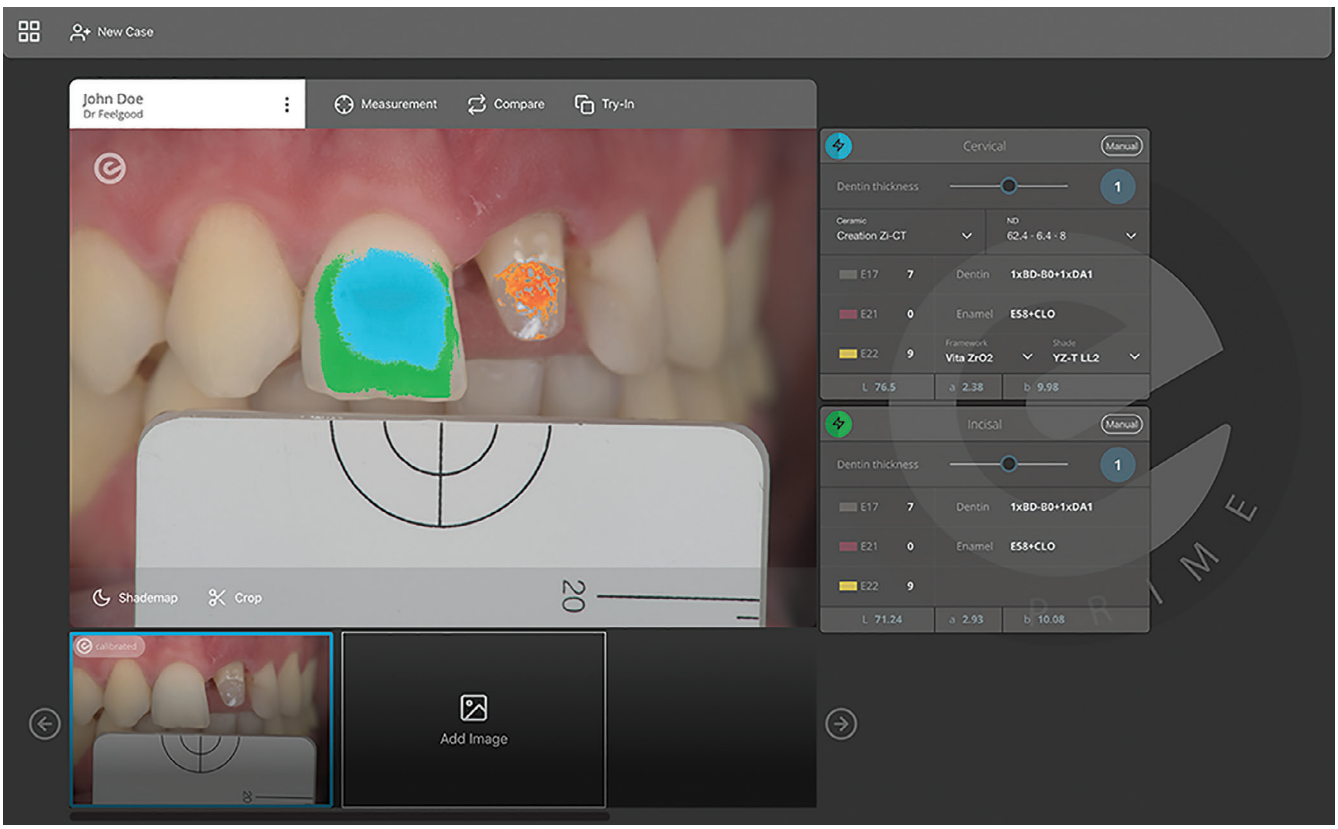

FIGURE 9 The desired target shade is obtained through image analysis using artificial intelligence algorithms for quantification of the most common tooth color with the help of statistical modeling. This process is carried out for two areas of the target tooth, the middle and lower third as well as for the incisal third and mixing recipes can be generated for a variety of popular ceramic systems and framework materials including all ceramic and metal ceramic systems or even for feldspathic veneers. It is also possible to quantify the actual substrate color to be considered for the mixing recipe

2.2.10 | Layering strategy

The main purpose of the eLAB protocol is to provide the aforementioned patient personal mixing recipe based on numeric quantification instead of relying on visual shade assessment. It is not designed to provide a complete layering map or to replace the skill and experience of a well-trained ceramist. Instead, the eLAB protocol is intended to compliment these attributes and to guide the ceramist toward a shade match that lies well within the threshold of clinical acceptability. As mentioned previously, many variations of only two archetypal types of layering strategies are in frequent use, either one of which is suitable for the eLAB protocol (Figure 11).

2.2.11 | Digital try-in

One of the most powerful features of the eLAB_prime application is its ability to perform a semi-automated digital try-in at any stage of the manufacturing process (ie, at the bisque bake or semi glaze stage) (Figure 12). This not only serves the purpose of obtaining a qualitative impression of the visual color match but also to utilize the advantages of the CIELAB color space. The use of the ranking scale by Paravina et al. makes it easy to determine the color difference for evaluation (Figure 13). Practical corrections can thus be carried out via the targeted application of stains.

2.2.12 | Integration

Upon integration, the eLAB system provides the advantage of objective shade evaluation and communication for adjustments if needed. The case presented here did not require any adjustments and could be cemented during the try-in appointment. Precise shade evaluation was carried out a few weeks later showing a near excellent clinical color match (Figure 14). The overall visual appearance was also esthetically pleasing despite some challenges like a congenically missing maxillary lateral (Figures 15 and 16).

FIGURE 10 It is also possible to quantify the actual substrate color to be considered for the mixing recipe

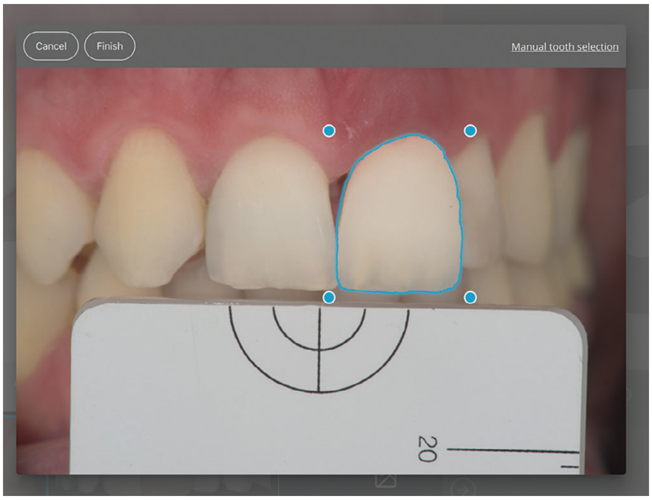

FIGURE 12 The main purpose of the eLAB protocol is to guide the ceramist toward a shade match that lies well within the threshold of clinical acceptability by combining quantification with traditional skills

FIGURE 11 The main strength of the eLAB system lies in its ability to provide individual shade matching recipes. Only few standard-shaded dentin powders (ie, Bleach 1, A1, A2, A3, D2) provide the foundation for trichromatic subtractive color mixing. A set of high precision instruments is used to portion three types of ceramic stains which can be mixed into any ceramic system regardless of its vitrification temperature or coefficient of thermal expansion (CET)

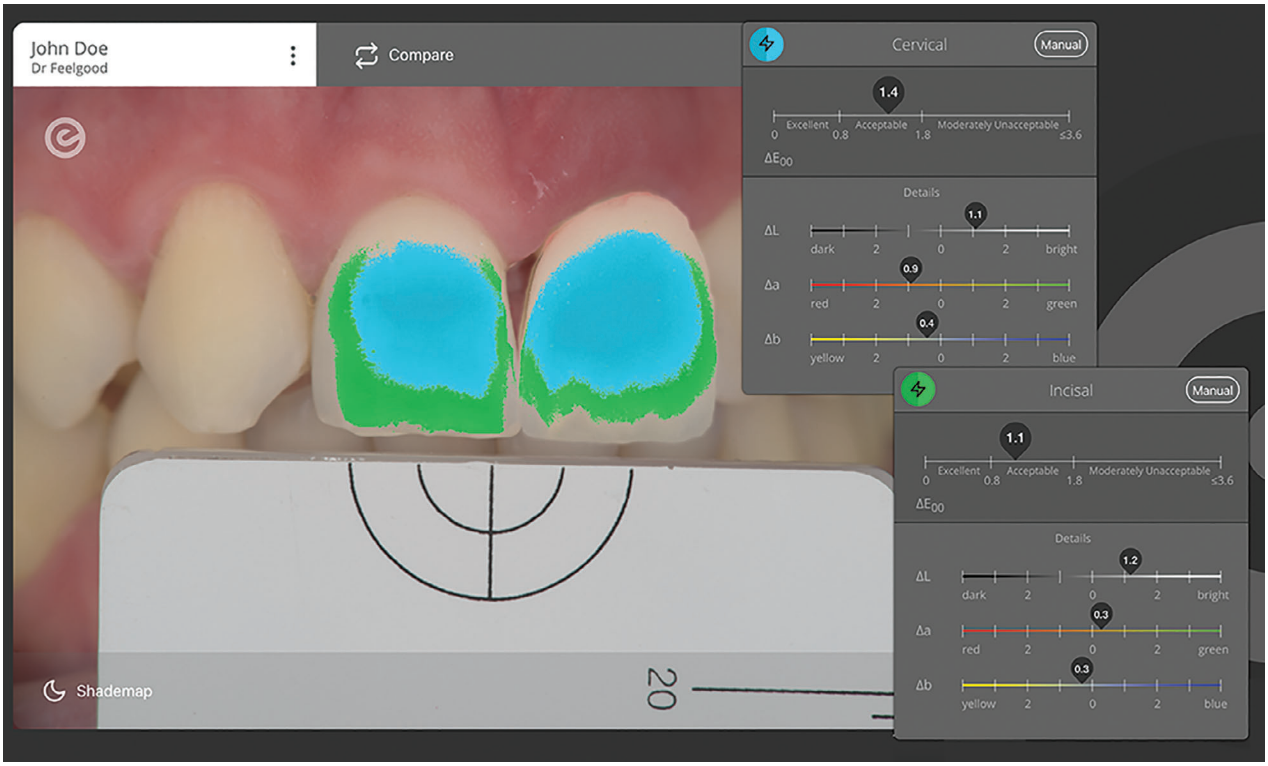

FIGURE 13 One of the most powerful features of the eLAB_prime application is its ability to perform a semiautomated digital try-in at any stage of the manufacturing process. This not only serves the purpose of obtaining a qualitative impression of the visual color match but also to utilize the advantages of the CIELAB color space

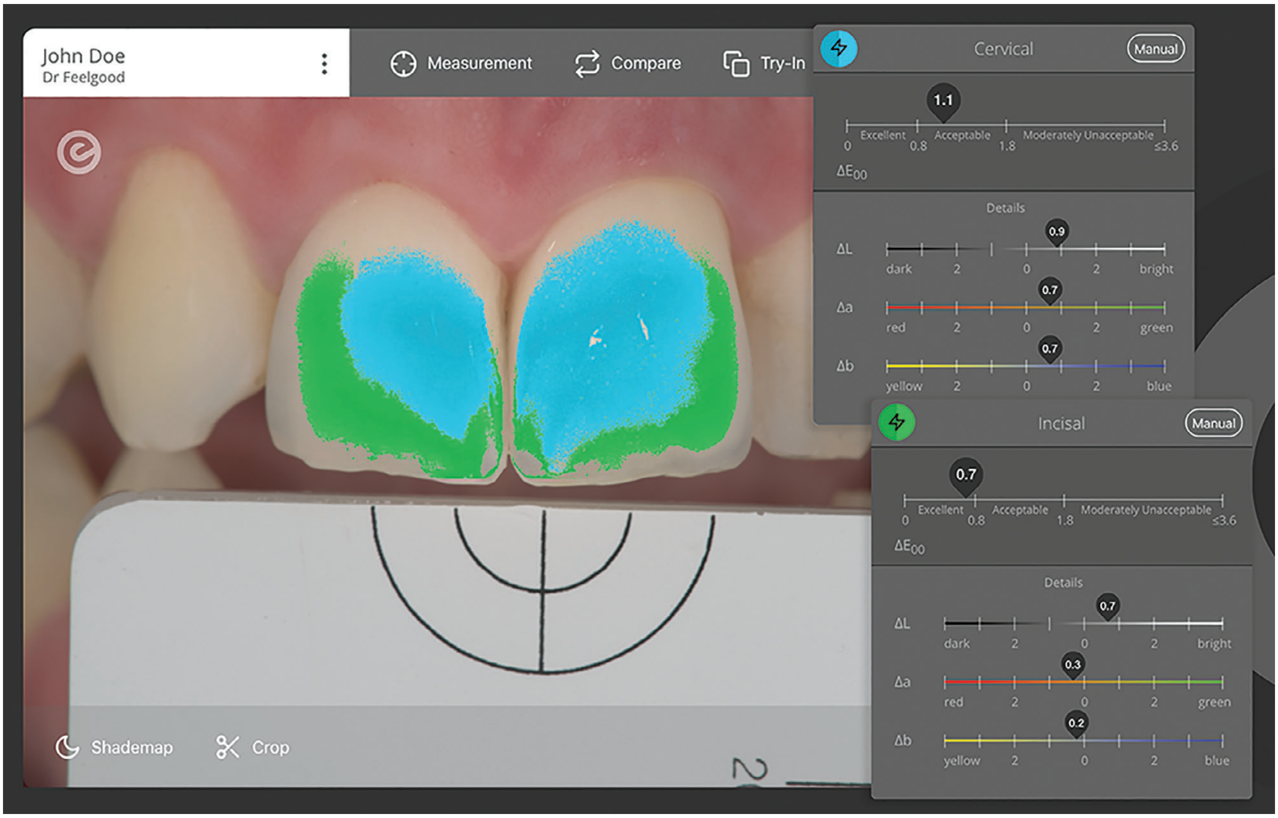

FIGURE 14 The use of the ranking scale by Paravina et al makes it easy to determine the color difference for evaluation a few weeks later, showing a near excellent clinical color match

FIGURE 15 The overall visual appearance was also esthetically pleasing despite some challenges like a congenically missing maxillary lateral

FIGURE 16 The overall visual appearance was also esthetically pleasing despite some challenges like a congenically missing maxillary lateral

3 | DISCUSSION

Today, colorimetric measurements can be carried out with digital cameras on diffusely scattering objects with uneven geometries or complicated shapes and structures. This task would otherwise present a tedious and costly challenge to overcome with photo spectrometers.[31] This case report addresses a new approach to objective shade communication and shade reproduction in dentistry, based on numeric quantification obtained from standardized RGB images, and the formulation of a patient personal shade recipe using trichromatic subtractive color mixing laws,[32] thus abandoning the use of visual assessment and shade guides entirely. This approach is currently enjoying increasing popularity for its ease of use, reliability as well as for its practically oriented features like its imaging ability or the digital try-in.

The measurement of heavy light scatterers like teeth presents a particular challenge due to a phenomenon referred to as "edge loss." It describes a loss of light due to its emergence outside of the detector field which is hence excluded from quantification. To avoid this, measurements are best carried out from an appropriate distance which does not interfere with the illumination.[33] This particular requirement is met by the eLAB protocol. More recently however, advanced research has been conducted in the area of Biophotonics for the purpose of determining the radiative transport through different types of diffusely scattering media like tissue[34] or dentin.[35] This has revealed a complex relationship between four optical parameters. They include the refractive index of the medium under consideration as well as the scattering and absorption coefficients and the scattering phase function which represents the scattering angular distribution.[36] Monte Carlo simulations are used to solve the radiative transport equation (RTE) for diffusely scattering media under consideration,[37] to predict their appearance under any incident light condition and viewing angle. This approach renders the evaluation of the optical appearance of natural teeth based exclusively on the concept of *color* (ie, absorption and scattering), rather one-dimensional because important components describing the radiative transport are simply ignored. Thus, a limitation of any currently available color quantification system intended for the use in dentistry, including the eLAB system, is that measured values for CIEDE color difference between a restoration and a natural tooth may suggest an imperceptible shade match, which yet contradicts dynamic visual observation under the given incident light conditions in the dental office or elsewhere. The origins for these complications are to be found in fundamental differences in material properties between dental hard tissues and dental ceramics. Especially discrepancies of the scattering phase function, which is largely isotropic in the case of dental materials,[38] can lead to considerable differences in radiative transport compared to dental hard tissue. This needs to be recognized by general practitioners and especially by prosthodontists who tend to be hypercritical when it comes to evaluating the quality of shade matches clinically.[39] Instead, the threshold recommendations for perceptibility and acceptability by Paravina et al serve as a practical compass for shade evaluation under the given limitations and the eLAB system can help to determine these parameters objectively using the advantages of the CIELAB color space.

Despite the aforementioned limitations, the eLAB system and other systems based on shade quantification may at last pave the way for becoming the new standard for best practice for objective shade communication in dentistry.

4 | CONCLUSION

The eLAB system provides a systematic approach to shade matching in dentistry based on numeric quantification in combination with traditional skills.

ACKNOWLEDGMENT

We are indebted to Dr Hrvoje Buntak from Denta Centar in Zagreb, Croatia for providing the clinical case depicted in this contribution.

CONFLICT OF INTEREST

Sascha Hein is the principal director of Emulation S.Hein in Freiburg, Germany which distributes some of the products mentioned in this contribution.

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