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How many tooth colors are there?

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ABSTRACT

Objectives: This study aimed to estimate the number of distinct tooth colors using a large dataset of in-vivo CIELAB measurements. It further assessed the coverage error (CE) and coverage error percentage (CEP) of commonly used shade guides and determined the number of shades needed for an ideal guide, using the Euclidean distance (ΔEab) and thresholds for clinical perceptibility (PT) and acceptability (AT) as evaluation criteria.

Methods: A total of 8153 untreated maxillary and mandibular anterior teeth were measured in vivo using calibrated dental photography. Cardinality was applied to determine the number of unique natural tooth colors. The CE and CEP were calculated for the Vita Classical and Vita 3D-Master shade guides, while the cardinality method was also used to estimate the number of shades required to adequately cover the estimated gamut of natural tooth colors.

Results: The cardinality analysis revealed 1173 unique natural tooth colors. The CE for the Vita Classical shade guide was 4.1 ΔEab, with a CEP of 75 % beyond AT, while the 3D-Master shade guide had a CE of 3.3 ΔEab and a CEP of 70 % beyond AT. Based on cardinality computation, 92 discrete shades are required to adequately cover the estimated gamut of natural tooth colors with a CE of 1.2 ΔEab and CEP of 0.3 % beyond AT.

Conclusions: Cardinality computations estimated 1173 unique tooth colors while 92 discrete shades are estimated for full coverage. Such a number is impractical for physical shade guides, but new digital tools and 3D printing may offer future solutions. Both, the Vita Classical and 3D-Master shade guides do not fully represent the range of natural tooth colors.

Clinical significance: This study highlights the limitations of existing shade guides and underscores the potential for new developments.

1. Introduction

Accurate shade matching, particularly for challenging single anterior restorations, remains a critical task in restorative dentistry. Clinicians frequently report complications with shade matching [1–3], which often leads to patient dissatisfaction [4] and a significant re-make rate [5]. Studies which have compared the benefits of instrumental shade measurement with visual shade selection [6–8] commonly agree that the latter is more subjective and less reliable [9,10], yet it remains the most common approach to shade matching in dentistry [11]. Vita Classical and Vita 3D-Master are the two most popular shade guides for visual shade selection [12].

Despite their widespread use, the coverage error (CE) or its percentage (CEP) associated with these shade guides (i.e., the average distance between a natural tooth color and the closest shade tab [13]) often exceeds the threshold for clinical acceptability [13–22]. Studies have analyzed sample populations ranging from 60 [18] to 2067 [19] human teeth with reported CEs between 2.5 [22] and 8.4 [20] ΔE_{ab} units. This significant error has led to the development of hypothetical shade guides designed either to reduce the CE with the same number of shade tabs [16] or to maintain the same error with fewer tabs [14,23], thereby simplifying the shade matching process. However, none of these

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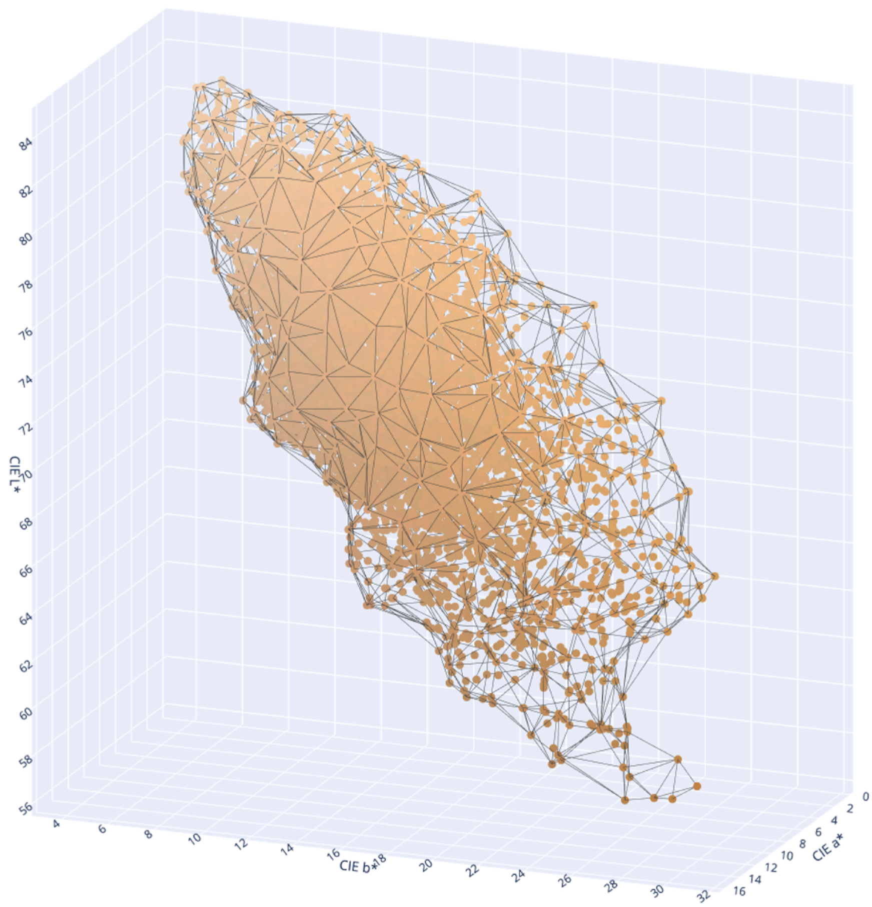

Fig. 1. Alpha hull representation of volume enclosing 8153 natural tooth colors measured in vivo in CIELAB color space ($\alpha = 2\ \Delta E_{ab}$).

suggested improvements have found their way into new shade guides to enhance clinical practice. Determining the optimal number of samples for an ideal shade guide requires consideration of several factors, including the chosen visual acceptance threshold and the gamut of natural tooth colors, which remains elusive.

Cardinality is a mathematical concept that counts the number of distinct elements in a set [24]. Understanding the cardinality of natural tooth colors—how many unique, visually distinguishable tooth colors exist—based on measured CIELAB data from a representatively large population allows for the estimation of the number of shades needed for an ideal shade guide, improving representation and shade matching accuracy in dentistry.

The eLAB system is a color measurement tool that utilizes calibrated RAW images captured with a DSLR or mirrorless camera equipped with a macro lens and a ring or lateral flash [25]. Cross-polarization is used to eliminate specular reflections from the tooth surface [26] to allow for unobstructed color measurement [27–29] regardless of ambient light conditions [30]. For consistent tooth color representation across different digital cameras, a gray reference card is used, equipped with a color checker consisting of 22 patches [31] which serve for computing a transformation matrix that relates their sRGB values to known CIELAB values. This matrix is then applied to the entire image, converting sRGB to CIELAB and subsequently back to sRGB for accurate color rendering based on the reference CIELAB data [32]. This process ensures standardization across images from different cameras, allowing for direct comparison of tooth colors [33]. The eLAB system has been used to detect tooth color changes comparable to spectrophotometric analysis [34] and to monitor changes in white spot lesions (WSLs) as a function of treatment [35]. It has been used to analyze the shade variance of identically labeled direct composite materials from different manufacturers [36] and to assess the efficiency of at-home bleaching protocols [37]. A recent multicenter study demonstrated that the eLAB system achieved visual-instrumental agreement with no significant difference in performance compared to other commonly mentioned color measurement devices including spectrophotometer, multispectral cameras and tele-spectroradiometers [38].

The aims of this study were to first estimate the number of distinct tooth colors using a large dataset of in-vivo CIELAB measurements obtained from the eLAB system, then to identify a set of hypothetical 'super shades' to best cover the gamut of natural tooth colors, and finally to assess the CE, CEP, and the frequency of individual shades for both, the most common shade guides and the identified super shades.

2. Material and methods

2.1. Study design

This study was conducted following the approval of the research ethics committee, granted under reference number 1366. All procedures adhered to ethical guidelines and received necessary consent from participants, in compliance with the EU's General Data Protection Regulation (GDPR).

2.2. Data collection

Over 29 months, a total of 121,198 RAW images were collected from users of the eLAB_prime shade matching software (Emulation, Freiburg, Germany) across 98 countries worldwide. A multi-step AI-based approach was utilized to vet the data pool. A convolutional neural network was used to assess and filter images based on quality metrics

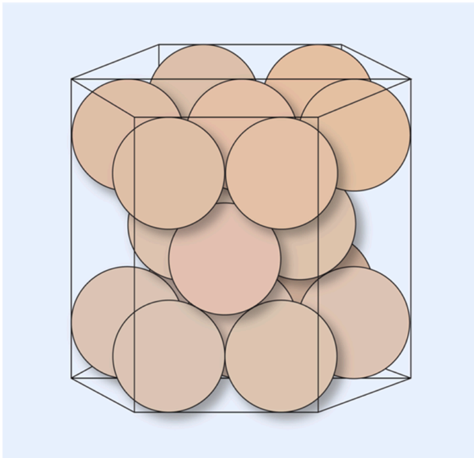

Fig. 2. Example of hexagonal close-packed sphere model of visually distinguishable tooth colors used in this study. The diameter of each sphere corresponds to the clinical threshold chosen.

[39,40], such as correct exposure, presence of a grey reference card. For duplicate detection, feature extraction followed by clustering and perceptual hashing was used [41,42]. Object detection and semantic segmentation models [43] identified and excluded images with artificial restorations. The resulting pool of images was further examined visually by five experienced master dental technicians using the eLAB_prime software (Emulation, Freiburg, Germany). This resulted in a total of 2038 RAW images to be included for the CIELAB tooth color measurement of 8153 untreated maxillary and mandibular anterior incisors.

Color measurements were taken across the incisal and medio-cervical regions of the labial surface, providing a broad representation of the tooth's color. The final color was calculated as the average of these CIELAB values, consistent with methodologies used in other studies [37, 44–46].

For each Vita Classical (VC) and 3D Master (3D) shade tab, their colorimetric data were obtained using the eLAB system, following the same method used for the natural tooth color population. The reference numbers for the shade guides were +J017B0271 for VC and +J017B36002 for 3D.

2.3. Computation of cardinalities

The required condition to answer the question of how many tooth colors exist is that each color is unique, with no other color matching it. In a finite, countable set of numbers—such as tooth colors, which occupy only a small region of the CIELAB color space—cardinality simply refers to the number of unique elements in that set. Therefore, working with a restricted set of elements makes this task manageable, unlike trying to determine how many colors there are in total, from a set of infinite or practically infinite elements [47,48].

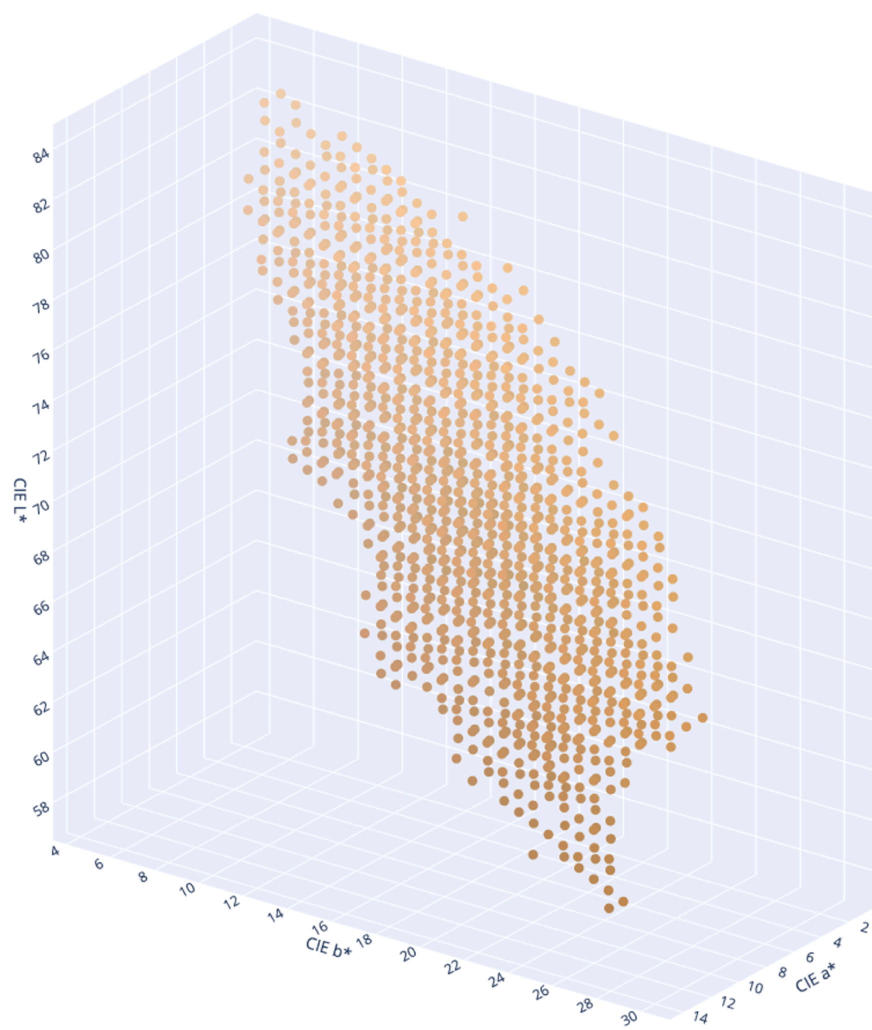

Fig. 3. Depiction of cardinalities revealing 1173 unique natural tooth colors.

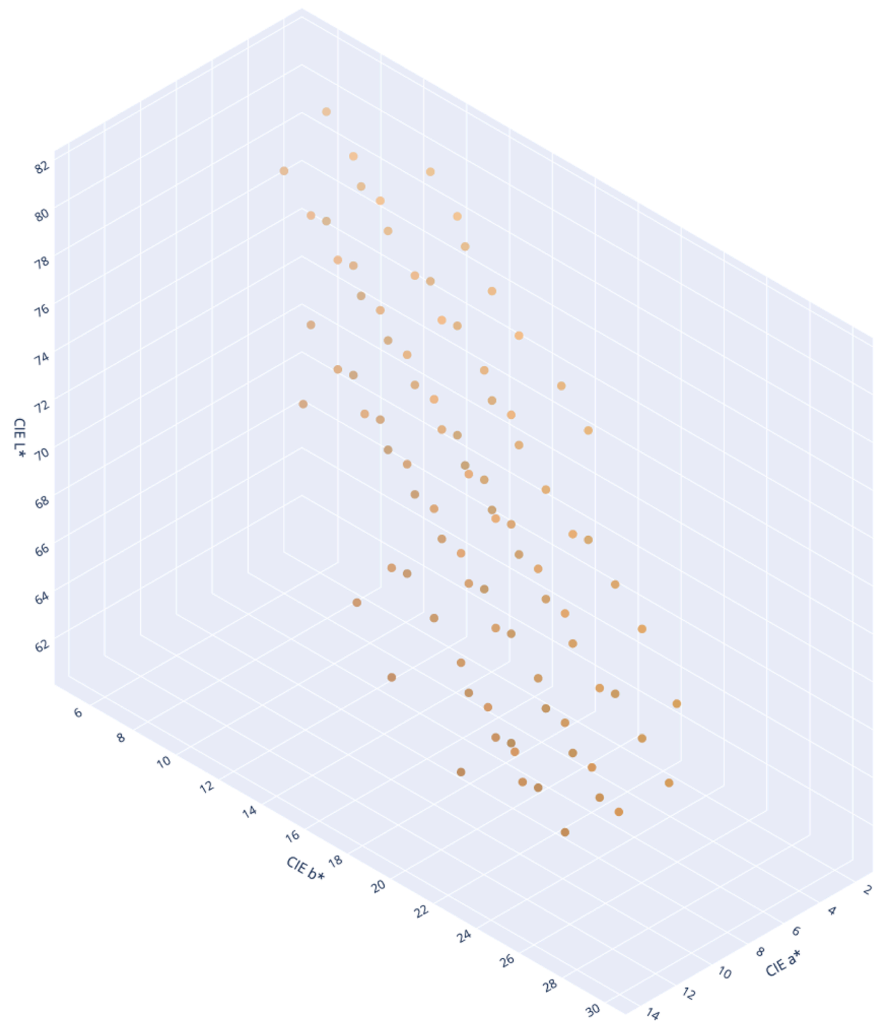

Fig. 4. Representation of 92 super shades, indicating minimum number of shade tabs required for an ideal shade guide.

First, an appropriate color difference metric needed to be nominated. In this case the CIE 1976 ΔE_{ab} formula was chosen because a recent multicenter study [38] demonstrated that the eLAB system achieved an outstanding 82 % visual-instrumental agreement using ΔE_{ab}, outperforming much more complex color difference equations such as CIEDE2000 and CAM16-UCS.

Next, a volume space containing 8153 natural tooth coordinates S in CIELAB color space was used for the efficient construction of a convex hull called an α-shape which presents the hull containing all points of S such that no more than three hull vertices are contained in a sphere of radius α [49]. In this context, α is a sufficiently small, positive real number chosen to construct a boundary of the natural tooth color gamut such that its value represents a desired level of tolerance to concavity. In the present case a value of $\alpha = 2$ ΔE_{ab} units was chosen for the construction of the convex hull since it provided a good balance between the density of S and the low thresholds used for perceptibility and acceptability in dentistry [50] (Fig. 1). Then, a custom Python routine (Python Software Foundation, Wilmington, DE, USA) was employed to quantify the cardinality of the most densely packed set of unique colors in the α-shape of natural tooth shades, ensuring that the difference between any two points is greater than or equal to the threshold for clinical perceptibility, set at 1.2 ΔE_{ab} units [50]. This was achieved with a hexagonal closed sphere-packing model [51], where each tooth color was represented by a sphere with its center at that color and with a diameter matching the corresponding ΔE_{ab} threshold value of 1.2 ΔE_{ab}. The number of non-overlapping spheres within the dataset indicated the cardinality, providing a measure of distinct tooth colors (Fig. 2).

2.4. Identifying super shades

To identify a set of 'super shades,' representing hypothetical tooth colors that best cover the range of natural tooth colors, the cardinality calculation was repeated. The goal of an ideal shade guide is to provide adequate coverage of the natural tooth color gamut within the clinically acceptable range, while remaining as practical as possible. Therefore, the same convex hull and sphere packing model was employed, but with the sphere diameter was set to 2.7 ΔE_{ab} units corresponding to the threshold for clinical acceptability [50].

2.5. Computation of coverage error and coverage error percentage

To compute the CE and the CEP for the VC and 3D shade guides, the color differences between each of the 8153 sample tooth colors and each reference shade tab from both shade guides were calculated under Illuminant D65 and for the CIE 1931 standard colorimetric observer [52] using the ΔE_{ab} color difference equation in MATLAB (MathWorks, Natick, MA, USA). For each natural tooth color, the reference shade tab with the minimum color difference was identified, and the frequency of each reference shade tab being the closest match was recorded. The CE was determined by averaging the minimum ΔE_{ab} values across all sample tooth colors using this formula:

Table 1
CE and CEP along with standard deviations (SD) for the Vita Classical (VC) and for the 3D-Master (3D) shade guides respectively.

Shade Guide	CE (ΔE_{ab}) (SD)	CEP ≤PT (SD)	CEP >PT, ≤ AT (SD)	CEP >AT (SD)
VC	4.1 (1.8)	1.1 % (0.2)	24.3 % (0.4)	74.6 % (1.6)
3D	3.3 (1.4)	3.0 % (0.2)	27.8 % (0.7)	70.3 % (1.2)
Super Shades	1.2 (0.4)	33.8 % (0.2)	65.9 % (0.3)	0.3 % (1.5)

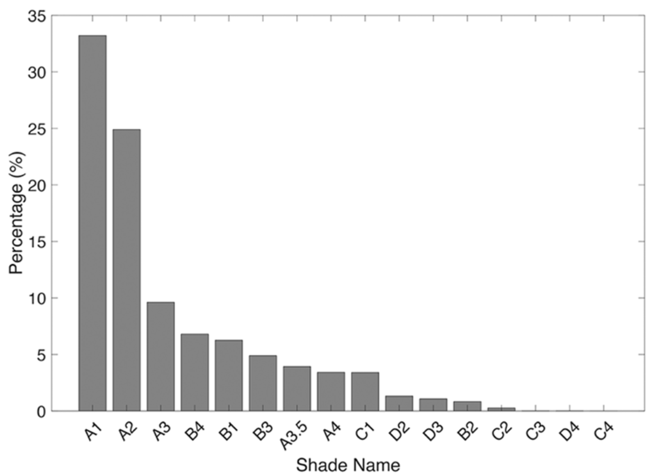

Fig. 5. Percentages of shade frequency for Vita Classical shades.

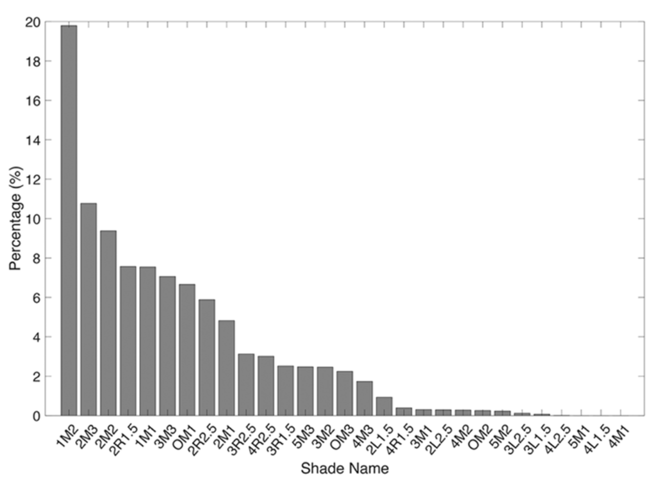

Fig. 6. Percentages of shade frequency for Vita 3D-Master shades.

$$CE = \frac{\sum_{i=1}^{n} \min(\Delta E_i)}{n}$$

To express the CEP, the proportion of occurrences for each shade tab was calculated and normalized by the total number of sample tooth colors using this formula:

$$CEP_j = \left(\frac{occurences_j}{n}\right) \times 100$$

The resulting percentages were then sorted from high to low, to facilitate a comparative analysis. Accordingly, the same computations were carried out to evaluate the effectiveness of super shades.

3. Results

3.1. Cardinalities and super shades

Based on the threshold for clinical perceptibility (ΔE_{ab} 1.2), the computation of cardinalities revealed 1173 unique natural tooth colors (Fig. 3) and 92 super shades when the thresholds for clinical acceptability (ΔE_{ab} 2.7) was used, representing the minimum number of shade tabs that an ideal shade guide would need (Fig. 4).

3.2. Coverage error of shade guides and super shades

Table 1 lists the CE and CEP results for VC, 3D shade guides and the super shades, along with their standard deviations. Fig. 5 shows the percentages for the most common shades of the VC shade guide while Fig. 6 displays the corresponding values for the 3D shade guide and Fig. 7 for the super shades.

4. Discussion

This study aimed to estimate the number of distinct tooth colors based on 8153 in-vivo CIELAB measurements and to determine the CE and CEP of the most common shade guides alongside a set of hypothetical 'super shades'.

Previous studies have reported similar CEs for the VC and 3D shade guides, averaging 4.4 ΔE_{ab} and 4.2 ΔE_{ab}, respectively [13–22,53–57]. Our findings align with these reports, confirming that while widely used, current shade guides are limited in covering the full range of natural tooth colors. Using cardinality computation, this study estimated that a set of 92 super shades could potentially cover the gamut of natural tooth colors with a CEP of only 0.3 % outside the threshold for clinical acceptabitly.

The reported frequencies of individual shades with the lowest CEP also vary considerably. The findings of this study are generally in agreement with those of Ruiz Lopez et al. [22] and Paravina et al. [16] but differ from Bayindir et al. [15] and Tabatabaian et al. [21], who both reported that the VC shade 'D3' had the lowest CEP frequency.

While training programs for visual shade matching have been

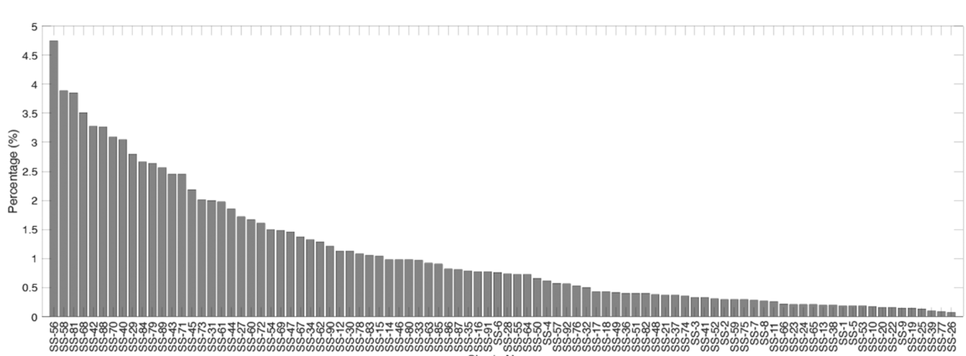

Fig. 7. Percentages of shade frequency for 92 super shades (SS).

proposed [58–61] the present study highlights the persistent challenges in achieving accurate shade matches, even with training. Recent research has also focused on evaluating the accuracy of shade measurement devices [7,9,62–64] and, more recently, intraoral scanners [7,65,66]. However, the results of this study suggest that discrepancies in shade matching may stem more from the coverage error of shade guides than from device accuracy [67].

Although a physical shade guide consisting of 92 discrete shades would be highly impractical, the insights from the present study could prove beneficial in the near future with the rise of digital tools for shade matching [31,68] and new technology like 3D printing [69].

Tooth color appearance is a complex phenomenon [70] and cannot be fully captured by CIELAB values alone. In clinical practice, acceptance or rejection of a restoration often depends on situational factors that cannot be wholly accounted for by visual thresholds alone. For instance, a clinical study by Ballard et al. [57] found that 94 % of patients were at least satisfied or extremely satisfied with a clinical shade-match that was well beyond the clinical acceptability threshold assumed in the present study.

It is also important to recognize that the results of the cardinality computation depend on specific input parameters, such as the definition of alpha-radii and the chosen visual threshold values. Consequently, the results are accurate for color differences computed using Euclidean distance but may not hold for other color difference equations. This is because the volume of the alpha hull, and how many spheres can be packed within it, is determined by the visual thresholds and the color difference equation used, which in turn define the diameter of each sphere. However, even with variations in these parameters, the overall finding remains consistent: a significantly larger number of shade tabs is needed for an ideal shade guide than is currently available.

5. Conclusion

To the best of our knowledge, the present study comprises the largest gamut of natural tooth colors ever published. Unfortunately, the results show that the likelihood of selecting a shade that is either clinically imperceptible or at least acceptable is one in four for the VC shade guide (25 %) and nearly one in three for the 3D-Master shade guide (31 %). On the other hand, a physical shade guide to achieve almost complete coverage is estimated to require 92 discrete shade tabs. These findings highlight the inherent challenges when trying to select the right shade during daily clinical practice.

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