The effect of enamel porcelain thickness on color and the ability of a shade guide to prescribe chroma

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ABSTRACT

Objective. To test the null hypothesis that there is no color change when enamel porcelain thickness is changed and to evaluate the ability of a shade guide to prescribe chroma.

Methods. Three shades (3M1, 3M2 and 3M3) were selected from a Vitapan 3D master shade guide. Five disk specimens were prepared for each shade, consisting of three layers (opacious dentin, dentin and enamel) at thicknesses of 0.6, 0.8 and 0.6 mm, respectively. The color of each disk was measured using a spectrophotometer. Enamel porcelain was reduced in thickness to 0.3 mm and porcelain disks were remeasured.

Results. Reducing the enamel thickness of porcelain disk specimens significantly increased \( L^* \) \((p < 0.05)\), \( b^* \), metric chroma and hue angle \((p < 0.001)\). For the three shades studied (3M1, 3M2 and 3M3) \( L^* \) values were not significantly different \((p > 0.05)\) and chroma increased for 3M1 with the lowest chroma to 3M3 with the highest chroma, which is in line with the shade guide specifications. Although statistically significant \((p < 0.001)\) changes in hue angle between the three shades were small (less than 3° overall). The difference in chroma between the three shades 3M1, 3M2 and 3M3 was greatest for the thin enamel layer than the thick enamel layer.

Significance. A change in enamel thickness from 0.6 to 0.3 mm resulted in a three-unit change in \( L^* \) and metric chroma and a 4° change in hue angle. A change in enamel porcelain thickness will have a greater effect on higher chromatic shades than those with lower chroma. The ability of the shade guide to prescribe chroma was demonstrated but this could be offset by an anomalous enamel thickness.

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1. Introduction

The increase in patient awareness and demand for aesthetic restorations is challenging for the dental team. Dentists are required to provide the laboratory with a correct shade match and the technicians have to reproduce this. The difficulty of an observer to perceive and reproduce a correct color match has previously been reported [1–3]. On the other hand, there are a number of variables in laboratory reproduction of the shade prescribed by the dentist. The thickness of different layers of porcelain, metal substrata and the porcelain batch are all factors, which may...
contribute to a color difference in the porcelain build up [4].

Whilst previous workers have studied the effect of thickness, firing, glazing, aging, metal or ceramic substrate with dentinal and opaque porcelain on the final color of restoration [4–15], the effect of enamel porcelain thickness has not been investigated.

Shade guides should have basic requirements in color matching including the logical arrangement within the color space and adequate distribution within color space of natural teeth [16]. The classical Vitapan shade guide, which is widely used only enables the clinician to prescribe hue (A–D). Value and chroma are linked together. When value decreases, chroma increases, i.e., A1 has high value and low chroma where A4 is the reverse. The Vitapan 3D-Master shade guide is a development of the Classical Vitapan shade guide, and is based on a systematic colorimetric principle of representing three-dimensional color space.

Evaluation of color can be achieved by two means: qualitative by subjective visual matching or quantitative (objective). The visually perceived color space consists of three-dimensions represented by lightness (black to white), hue (whether it is red, green, blue, etc.) and saturation or chroma (high chroma or saturation indicates a pure color, whereas, a low chroma or saturation indicates a color that contains more grey) [17]. In the Munsell color system, the three correlates of lightness, hue and saturation are value, hue and chroma [18]. This evaluation depends on the ability of human observers to detect color differences [1–3]. The CIE (Commission International de l’Eclairage) specifies methods for the instrumental measurement including illumination/viewing geometry and quantification of color [19]. The CIELAB color system describes the color of an object in terms of its position in three-dimensional space where the three axes are lightness (L’), red–green axis (a’) and yellow–blue axis (b’). Quantitative measurement of L’, a’ , b’ can be obtained from reflectance spectrophotometers or colorimeters with standard CIE illumination viewing geometry [19]. However, their intraoral use has some limitation related to the size, curvature of teeth, and the color difference across the tooth surface [20]. A number of dental color measurement instruments are available in the dental market, which may improve the shades of dental restoration but validation studies are needed to support their use.

There is very limited scientific literature available regarding the layering of dental porcelain and the effect upon the resultant color. Therefore, the aims of this study were to test the null hypothesis that there is no color change when enamel porcelain thickness is changed and to evaluate the ability of a shade guide to prescribe chroma.

2. Materials and methods

Three shades (3M1, 3M2 and 3M3) were selected from the 3D shade guide (Vitapan 3D-Master VITA Zahnfabrik, Bad Säckingen, Germany). This shade guide consists of 26 shades (compared to 16 shade tabs in the original), arranged (as claimed by manufacturers) in five levels of lightness (1–5). Within each lightness, there are three hue groups [L, M, R], with some limitation. For M-hue at a specific lightness level, shades only differ in chroma. For example, for shade 3M2, the first number (3) represents level 3 lightness, the letter M represents M hue and the last number (2) represents level 2 chroma. The selected shades were chosen as they are specified as representing three levels of chroma of the same hue and value. A total of fifteen disk specimens of the three shades of dental porcelain were constructed and all disk specimens were initially 2 mm thick to simulate the clinical thickness. They consisted of three layers each of 0.6 mm opacious dentin, 0.8 mm dentin and 0.6 mm enamel porcelains (Vitadur Alpha, VITA Zahnfabrik, Bad Säckingen, Germany). The layers were obtained at consistent thickness by using a set of master patterns. Five disk specimens were prepared for each of the shades to determine variations in color between samples of the same shade.

2.1. Preparation of refractory casts

A 22 mm diameter stainless steel washer of 2 mm thickness with an internal diameter of 12 mm was mounted on a lathe and the inner surface turned to widen the inner diameter to 13 mm at a depth of 0.6 mm. A second similar adjustment was made on the opposite side of the washer leaving a ridge 0.8 mm thick (Fig. 1a). A wax cylindrical disc was secured to one side of this washer with sticky wax (Fig. 1b). An impression was then taken of the washer using polyvinylsiloxane impression material (Fig. 1c). Following removal of the original washer, the original washer and wax base was removed and the mould inverted (Fig. 1d). Refractory material (Vitaturnest VITA Zahnfabrik, Bad Säckingen, Germany) was mixed using a vacuum mixer (30 g powder, 7 ml liquid) and poured into the impression. The refractory casts were fired in a furnace (Dentsply DeTrey, Dreieich, Germany) according to the manufacturer’s recommendations. A total of 15 refractory casts were produced for porcelain disk construction (Fig. 1d).

2.2. Porcelain build-up

Each step in the inner surface of the refractory cast was marked around the rim with red-wax pencil to improve visibility before soaking them in water prior to the porcelain build-up. The porcelain powders were mixed with porcelain molding liquid and a blue food dye so that they could be distinguished from the white background of the refractory material. A moistened brush was used to apply each porcelain layer in small increments until it reached its step level. The porcelain disk specimens were fired in a porcelain furnace (Dentsply DeTrey, Dreieich, Germany) after each build-up according to the manufacturer’s recommendations. A corrective build-up for each porcelain layer and a second firing was necessary to compensate for firing shrinkage. After the three-layer build-up of dental porcelain (opacious dentin, dentin and enamel) had been completed, the disk specimens were then placed in the furnace for glaze firing (according to the manufacturer’s instructions).

2.3. Color measurements

Reflectance spectra data were measured for the fifteen porcelain disk specimens with 0.6 mm enamel layer thickness. The
enamel layer was then reduced in thickness to 0.3 mm using a fine diamond bur in a strait handpiece. Thickness was checked using a micrometer (±1 μm) (Draper, Japan) for the 15 disk specimens and color measurements retaken. Samples were accepted if the enamel porcelain thickness was 0.3 ± 0.01 mm. The disks were measured in dry conditions against the white background of the investment mold. The reflectance spectrophotometer (Monolight, Macam Photometrics, Livingstone, Scotland) used for color measurement consisted of a Model 6800 controller, with a 6100 monochromator, blaze 300 nm, 0.45 mm slit width, high gain photomultiplier detector controlled by Monolight software. The 45°/0° reflectance head was attached to the tungsten halogen light source and photomultiplier via fiber optics cable. The 45°/0° geometry used, as recommended by Seghi et al. [21], had a nominal 7 mm elliptical (8 mm major axis and 6 mm minor axis) 45° illumination area and 0° viewing area of 4.5 mm diameter.

The spectrophotometer was calibrated before color measurement for zero reflectance using a black plate in the light beam path and wavelength calibration using Helium–Neon laser source (peak between 632.75 and 633.00 nm). All measurements were made relative to a standard white tile (British Ceramic Research Association). This reference spectrum was taken to be 100% reflectance for future measurements. The reflectance spectra for the measured samples were used to calculate the CIE XYZ tristimulus values using built-in software. A 100% reflectance calibration was undertaken before each sample measurement to reduce possible instrumental drift. The measured reflectance spectrum of the disk specimens was obtained at 1 nm intervals and the CIE XYZ values were calculated for D65 illumination and a 2° observer curve using the built in software. The data was then imported into a spreadsheet (Microsoft office Excel 2000) and converted from X, Y and Z color tristimulus values to CIELAB color coordinates using the following equations.

\[
L^* = (116(Y/Yn)^{1/3}) - 16
\]  

\[
a^* = 500((X/Xn)^{1/3} - (Y/Yn)^{1/3})
\]  

\[
b^* = 200((Y/Yn)^{1/3} - (Z/Zn)^{1/3})
\]  

\[
C^*_{ab} = (a^*2 + b^*2)^{0.5}
\]  

\[
h^*_{ab} = \tan(b^*/a^*)^{-1}
\]  

\[
\Delta E^*_{ab} = [(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2]^{0.5}
\]

Xn, Yn and Zn are X, Y and Z values of a reference white for D65 illumination and 2° observer [19,22].

3. Statistical analysis

The data for the CIELAB values was analysed using two-way analysis of variance the main effect of enamel thickness (thick 0.6 mm or thin 0.3 mm) and porcelain shades (3M1, 3M2 and 3M3) and their interaction a split plot design for enamel thickness. The software used was Genstat 5 release 3.1.
The variation due to porcelain build up was evaluated in two ways. \( \Delta E \) values were calculated as the difference of each replicate from the mean of each shade thickness set. For this calculation CIELAB values \( L^* \), \( a^* \), \( b^* \) represent the average values for the replicates within a particular shade/enamel thickness and CIELAB values \( L'^* \), \( a'^* \), \( b'^* \) are the values for each of the five replicates for the same shade and enamel thickness. Also the coefficient of variations was calculated as the standard deviation expressed as percentage of the mean for each shade/enamel thickness set of replicates.

### 4. Results

The positions of the three shades with both thick and thin enamel in the three-dimensional CIELAB color space were shown in Fig. 2.

Reducing the enamel thickness resulted in statistically significant (\( p<0.01 \)) increases in \( L' \), \( b' \), \( C'_{ab} \) and \( h'_{ab} \) values and a statistically significant (\( p<0.001 \)) decrease in \( a' \) values (Table 1). The average \( \Delta E \) difference calculated on the basis of the changes within each disk was 5.6 for shade 3M1, 4.9 for shade 3M2, and 6.0 for shade 3M3. The three shades studied (3M1, 3M2 and 3M3) did not differ significantly in \( L' \) values (Table 1). There were statistically significant differences in \( a' \), \( b' \), \( C'_{ab} \) and \( h'_{ab} \) between the three shades. The \( a' \) values were lowest for 3M2 and highest for 3M3 (Table 1). The \( b' \) values showed a progressive increase from 3M1 through 3M2 to 3M3. Metric chroma also showed a similar progressive increase (3M1, 3M2 and 3M3), however, the hue angle did not show this progressive change. The hue angle was lowest in 3M1, and highest in 3M2. This order reflects the contribution of \( a' \), i.e., lowest in 3M2, highest in 3M3 to the hue angle (\( h'_{ab} = \tan^{-1}[b'/a'] \)).

There was a statistically significant interaction between enamel thickness for lightness (\( L' \)), \( b' \) and chroma (Table 1). The interaction for lightness shows that the effect of enamel thickness in increasing lightness is greater for 3M1 and becomes progressively less as we move through 3M2 to 3M3, such that there is no statistical significant difference in \( L' \) values due to thickness (Table 2). The interaction for \( b' \) and chroma show that for both of these the effect of enamel thickness is greater on 3M3 than 3M1. The effect of enamel thickness on lightness and chroma is clearly shown in Fig. 2. These interactions also show that the difference in lightness, \( b' \) and chroma is less marked when the enamel layer is thick (0.6 mm) than when it is thin (0.3 mm) (Table 2). The effect of thickness on chroma can be clearly be seen in Fig. 3, in this diagram the lines joining the points are shown for clarity and should not be taken as a linear relationship.

The variability in color due to restoration build up is shown in Table 3. Although the coefficient of variation (standard deviation expressed as percentage of mean value for the five replicates within a shade/enamel thickness set) for CIELAB values within some sets of replicates is low (less than 5%), other sets

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**Table 1 – The effect of porcelain enamel thickness and different porcelain shades on CIELAB parameters**

<table>
<thead>
<tr>
<th>Effect of enamel thickness</th>
<th>( L' )</th>
<th>( a' )</th>
<th>( b' )</th>
<th>( C'_{ab} )</th>
<th>( h'_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick</td>
<td>71.71</td>
<td>1.31</td>
<td>7.69</td>
<td>7.8</td>
<td>80.26</td>
</tr>
<tr>
<td>Thin</td>
<td>74.08</td>
<td>1.09</td>
<td>11.27</td>
<td>11.33</td>
<td>84.29</td>
</tr>
<tr>
<td>S.E.M</td>
<td>0.497</td>
<td>0.026</td>
<td>0.224</td>
<td>0.223</td>
<td>0.206</td>
</tr>
<tr>
<td>Significance</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect of porcelain shade</th>
<th>( L' )</th>
<th>( a' )</th>
<th>( b' )</th>
<th>( C'_{ab} )</th>
<th>( h'_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M1</td>
<td>72.27</td>
<td>1.21</td>
<td>7.70</td>
<td>7.80</td>
<td>80.91</td>
</tr>
<tr>
<td>3M2</td>
<td>74.74</td>
<td>0.99</td>
<td>9.00</td>
<td>9.07</td>
<td>83.30</td>
</tr>
<tr>
<td>3M3</td>
<td>71.67</td>
<td>1.40</td>
<td>11.73</td>
<td>11.82</td>
<td>82.62</td>
</tr>
<tr>
<td>S.E.M</td>
<td>1.230</td>
<td>0.071</td>
<td>0.306</td>
<td>0.308</td>
<td>0.220</td>
</tr>
<tr>
<td>Significance</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Significance of shade/enamel thickness interaction</th>
<th>( L' )</th>
<th>( a' )</th>
<th>( b' )</th>
<th>( C'_{ab} )</th>
<th>( h'_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

Within any column means with the same letters are not significantly different (\( p>0.05 \)). NS \( p\)-value > 0.05. \( L' \) represents lightness; \( a' \) red–green axis; \( b' \) yellow–blue axis; \( C' \) metric chroma; \( h' \) hue angle.

\* \( p<0.05 \).
\** \( p<0.01 \).
\*** \( p<0.001 \).
Table 2 – The interaction between the porcelain disk specimens’ shades and thickness of enamel porcelain

<table>
<thead>
<tr>
<th></th>
<th>Thick</th>
<th>Thin</th>
<th>Thick</th>
<th>Thin</th>
<th>Thick</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M1</td>
<td>69.87 a’</td>
<td>74.68 ab</td>
<td>6.83 a’</td>
<td>8.57 a</td>
<td>6.95 a’</td>
<td>8.64 a</td>
</tr>
<tr>
<td>3M2</td>
<td>73.39 a’</td>
<td>76.08 a</td>
<td>7.32 a’</td>
<td>10.69 b</td>
<td>7.41 a’</td>
<td>10.73 b</td>
</tr>
<tr>
<td>3M3</td>
<td>71.86 a (NS)</td>
<td>71.49 ab</td>
<td>8.91 b’</td>
<td>14.56 c</td>
<td>9.04 b’</td>
<td>14.61 c</td>
</tr>
</tbody>
</table>

Within any treatment column means with the same letters are not significantly different (p > 0.05). NS p-value > 0.05. Difference due to thickness within any shade are given in parentheses between the two means.

∗p < 0.05.
∗∗p < 0.01.
∗∗∗p < 0.001.

show high variability (Table 3). This variability is also shown by how ∆E values for individual specimens differ from the mean of their particular shade/enamel thickness group. For the disk specimens with thin enamel the variability tends to increase from 3M1, through 3M2 to 3M3. For disk specimens with thick enamel this is not as marked (Table 3).

5. Discussion

The ability to produce an aesthetic restoration depends both on the color matching ability of the clinician [1–3] and the skills of the technician during porcelain build up. This current experiment was designed primarily to study the effect of enamel thickness on the color of the final restoration and also (2) aspects related to the technician’s skills and (3) evaluation of the color space of the three shades studied (Vitapan 3D master 3M1, 3M2 and 3M3). It is evident from the results (Fig. 3) that these three aspects are interrelated. For example, the difference in chroma between three shades 3M1, 3M2 and 3M3 is greater when there is 0.3 mm enamel layer than when there is 0.6 mm enamel. These aspects will be discussed in detail later.

Natural teeth and porcelain restorations have translucent properties and thus the measurement geometry must be considered. There are a number of geometries specified by the CIE [19] and this results in different CIELAB color values when opaque materials, e.g., ceramic tiles are measured under different geometries [23]. A standard CIE 45°/0° geometry was used in this study which some workers [9] have recommended for tooth color measurement. Other workers [24] have recommended integrating sphere geometries. CIELAB values obtained from integrating sphere geometries with diffuse/0 geometry are less influenced by the surface texture, however, to reduce errors due to translucency the area illuminated must be larger than the area viewed [25]. Due to the lack of translucent standards there are relatively few published inter-comparisons between geometries [26]. The ratio of viewing area to illumination area as well as the geometry (integrating sphere or 45°/0°) are critical [24,26]. Although absolute CIE color values would be different and the magnitude of the differences for example due to enamel thickness would be different, the direction of the changes would be similar [26]. For translucent materials, different color values would be expected with geometry change and changes in the measurement area within geometry [26]. Therefore, any geometry used (i.e., 45°/0° or 0°/45°) in color measurement of translucent material must specify the illumination and viewing area in order to reproduce color values.

The technicians’ skills in obtaining the correct color for the restoration depend on a number of factors of which porcelain layer thickness, porcelain shade type, porcelain batch have been studied previously [4]. In the current study, the thickness of each layer was carefully controlled yet differences

Table 3 – Variation in ∆E values and coefficient of variation for CIELAB values within replicate sets

<table>
<thead>
<tr>
<th>Replicate</th>
<th>3M1 Thin</th>
<th>3M2 Thin</th>
<th>3M3 Thin</th>
<th>3M1 Thick</th>
<th>3M2 Thick</th>
<th>3M3 Thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆E&lt;sub&gt;(mean)&lt;/sub&gt;</td>
<td>1.57</td>
<td>1.28</td>
<td>6.22</td>
<td>3.92</td>
<td>4.45</td>
<td>5.11</td>
</tr>
<tr>
<td></td>
<td>2.01</td>
<td>3.43</td>
<td>2.6</td>
<td>0.87</td>
<td>0.22</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>2.19</td>
<td>3.76</td>
<td>4.01</td>
<td>2.25</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>2.47</td>
<td>3.08</td>
<td>1.60</td>
<td>0.38</td>
<td>5.99</td>
</tr>
<tr>
<td></td>
<td>2.15</td>
<td>0.33</td>
<td>3.19</td>
<td>0.84</td>
<td>2.36</td>
<td>2.86</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>4.23</td>
<td>3.73</td>
<td>5.67</td>
<td>1.87</td>
<td>2.49</td>
<td>6.66</td>
</tr>
<tr>
<td></td>
<td>7.57</td>
<td>7.06</td>
<td>10.76</td>
<td>16.39</td>
<td>8.49</td>
<td>25.44</td>
</tr>
<tr>
<td></td>
<td>5.18</td>
<td>5.20</td>
<td>15.79</td>
<td>6.47</td>
<td>14.78</td>
<td>8.65</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>0.70</td>
<td>1.17</td>
<td>1.33</td>
<td>0.72</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>5.24</td>
<td>5.16</td>
<td>15.6</td>
<td>6.48</td>
<td>14.71</td>
<td>8.69</td>
</tr>
</tbody>
</table>

∆E<sub>(mean)</sub> calculated as difference of individual disks form the mean value for each shade/enamel thickness set. Coefficient of variation (%) = standard deviation/mean × 100.
within a set of disks (i.e., same shade, same thickness) varied by up to six \( \Delta E \) units. Previous research has shown that body/opaque samples have a greater shade variation than opaque samples alone, since the opaque sample is closer to an ideal sample for color measurement whilst within translucent samples (body/opaque porcelain), light would be scattered and absorbed below the surface resulting in more variation in the color measurements \[8\]. Controlling color is therefore more difficult when the number of translucent layers is increased (e.g., dentin and enamel porcelain).

Changing the enamel thickness from 0.6 to 0.3 mm resulted in an average change of 5.5 \( \Delta E \). These changes in \( \Delta E \) are greater than the perceptible difference in \( \Delta E \) \[27\]. Since in the current study measurements were only made at 0.3 and 0.6 mm enamel it is difficult to predict the effect of other enamel thicknesses on CIELAB values. According to theory \[28\] the change in reflectance follows an exponential relationship with layer thickness. Thus a change from enamel thickness from 0.2 to 0.3 mm would have a greater effect on reflectance than a change in enamel thickness from 0.3 to 0.4 mm. The rate at which the reflectance of the enamel changes with distance depends on the absorption coefficient (\( k \)) and scattering coefficients of the enamel layer. The overall resultant effect on CIELAB values will depend on the spectral characteristics of the enamel as shown in this study and underlying dentine \[4–10,29\]. Thus as the enamel thickness increases the CIELAB values move from those of the underlying dentine towards those of the enamel. Therefore, in this study the greatest difference in CIELAB values existed between the enamel and the 3M3 shade, and thus chroma differences due to enamel thickness were greatest for 3M3 (Table 2 and Fig. 3). Such differences in appearance due to enamel thickness could be exploited to match different shades within a tooth. For example, if we consider shade 3M2 with an enamel thickness of 0.3, and we increase the enamel thickness in some areas we can achieve a chroma similar to that of 0.3 mm 3M1. Conversely if we decrease the enamel thickness of 3M2 with 0.3 mm enamel we can achieve a chroma similar to that of 3M3. This of course does not mean the appearance would be identical as there may be differences in \( L^* \) or hue as shown in this study.

McLean \[30\] stated that increasing the thickness of enamel porcelain reduces the value (CIE \( L^* \), lightness) and increases the translucency of the final restoration. In contrast, the present study has disagree with the previous statement and shown that increasing the thickness not only decreased \( L^* \) but reduced the metric chroma and the hue angle and therefore results in three-dimensional color change. The effect of dentin on color values was reported by Terada et al. \[10\] that as the thickness decreased, lightness (\( L^* \)) increased by approximately one \( \Delta L^* \) units, \( \Delta a^* \) by 0.2 units and 0.3 \( \Delta b^* \) by units. This would suggest that dentin would affect mostly the lightness. The difference in lightness between the five replicates could therefore be due to the combined effect of the dentin and enamel rather than the enamel alone.

The ability of the 3D shade guide to prescribe chroma at a given value and hue, however has been demonstrated within the limitations of this study. This is the first commercially available shade guide to take into consideration the three-dimensions of color. The clinician’s ability to select the correct shade more easily because of the logical arrangement of the 3D shade guide may be true, but further work is still required using the full range of shade tabs to determine if the increased number of possibilities makes the shade selection process more difficult. In addition, the use of this shade guide requires some knowledge of color science to achieve best results.

According to the manufacturer, the three shades used in this study represented the different level of chroma at a given value and hue. The results of this study clearly show differences in chroma between 3M1, 3M2 and 3M3. However, the difference in chroma depends on the thickness of the enamel (Fig. 3). In the color space occupied by these three porcelain shades, changes in lightness of around three to four \( L^* \) units corresponded to a 0.5 change in Munsell value.

Small but statistically significant differences were found in the hue angle (approximately 2°) between the three shades, this is considered of little clinical significance in low chroma samples such as teeth. The CIELAB system has been shown to have difficulty in hue angle for low tristimulus value ratios \[31\]. The perceived appearance of two tooth samples, which differ, by a hue angle of approximately 2° is very small near the centre of the circle (i.e., low metric chroma) but is considerable as metric chroma increases. Standardization of the thickness of the enamel would appear critical in prescribing chroma and the ability of the 3D shade guide to do so may therefore, be offset by failure to standardize the enamel thickness.

Studies on human enamel \[32\] showed that the \( h^* \) and \( a^* \) values of teeth from which the enamel was removed correlated strongly with the colors of the complete tooth, however, the correlation was poorer for \( b^* \) values. Further inspection of the data published \[32\] shows that removal of the enamel resulted in an increase in \( b^* \) values of approximately three \( \Delta b^* \) units at low \( b^* \) values and five \( \Delta b^* \) units at high \( b^* \) values. Overall, \( \Delta E \) values calculated from the plotted regression lines \[32\] due to removal of enamel are between five \( \Delta E \) and seven \( \Delta E \) units. Thus the changes in \( \Delta E \) found in our current studies where enamel was reduced from 0.6 to 0.3 mm, on a limited range of porcelain shades are in the same direction and of a similar magnitude to those found for a wider range of human teeth where enamel was removed.

Future research should consider not only the conventional layering of opaques, and dentinal porcelain (translucent porcelain) \[10,15,29\] but also include enamel porcelain as a three layer model when studying the effect of porcelain thickness on the final color. With a knowledge of the absorption (\( K \)) and scattering coefficient (\( S \)) of the enamel and the application of Kubelka–Munk theory would allow CIELAB values for any given enamel thickness to be predicted if the reflectance spectra of the background dentine/opaque layer was known.

When preparing teeth for ceramic restorations the current study reinforces the need for adequate reduction to allow for the correct proportion of different layers of dental porcelain (including enamel porcelain). It is also important for the clinician to appreciate that color changes will occur if crowns are re-contoured, as this will change the enamel porcelain thickness and will result in a three-dimensional color change. As demonstrated in this paper the change can be very significant (\( \Delta E \) approximately six units) which is perceivable by the human eye and regarded as an unacceptable difference \[27\]. The clinician should also recognize that a restoration with,
an initially, high chroma will show a greater color change after adjusting the enamel porcelain thickness and so should proceed with caution. On the other hand, if a technician is building up a crown with A4 shade, the enamel thickness of the dental porcelain would be more critical for the chroma of the restoration than if it is A1 shade.

6. Conclusion

Within the limitations of this study the following conclusions can be drawn:

- Reducing enamel thickness produced three-dimensional color changes (lightness hue angle and metric chroma), which were regarded as above the acceptable color tolerance for a dental restoration.
- A change in enamel porcelain thickness will have a greater effect on higher chromatic shades than those with lower chroma.
- The ability of the shade guide to prescribe chroma was demonstrated but this could be offset by an anomalous enamel thickness.

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REFERENCES