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Technical note

Metamerism in aesthetic prostheses under three standard illuminants – TL84, D65 and F

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Abstract

This study looks at the effect of metamerism in colour-matching and the assessment of multi-layered silicone rubber finger prostheses. The aim was to identify the choice of illuminants for colour matching the prostheses that would give rise to the least metameric effect between the prostheses and the human skin or the best colour match. The prostheses were prepared and colour matched to a fair-skinned subject under 3 reference illuminants – TL84, D65, F and a combination of illuminants – TL84, D65 and F. The prostheses were then measured for colour using a spectrophotometer based on the CIE indices L^*, a^*, b^* with each prosthesis assessed separately against the subject's index finger under the reference illuminants – TL84, D65 and F. The prostheses were also assessed by a panel of 50 observers and scored according to colour-match. Colour differences between the skin and prosthesis were measured in the illuminant under which the prostheses were prepared and then under the other reference illuminants. A relationship was obtained between the measured mean colour difference, ΔE^*, and the mean visual assessment score for each prosthesis. This paper points out the concerns related to the optical phenomenon of metamerism with the colour pigments used. This can affect the colour match of the prosthesis as perceived by the patient. The findings seem to suggest that this metameric colour difference can be minimised if the prosthesis is matched under a combination of lights, which were found to give the best-perceived match.

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Introduction

In the restoration of the upper limbs and maxillofacial region with aesthetic prostheses, an accurate colour reproduction is always crucial to acceptance and use. However, the quality of the colour match can differ when viewed under different light sources. Most often a good colour match between the prosthesis and the skin obtained under one light source may not have similar match under a different light source. This is attributed to the difference in the pigments present in the skin and in the prosthesis. This optical phenomenon, whereby the reflectance spectrum of objects with dissimilar pigment contents changes under different illuminant, is known as metamerism (Judd and Wyszecki, 1975).

The colour of human skin is mainly characterised by five pigments interspersed within its stratified architecture (Anderson and Parrish; 1981; Williams and Warwick, 1980; Agache *et al.*, 1989; Leow *et al.*, 1996). They are melanin (brown), melanoid (brown), and carotene (yellow to orange) in the dermis layers, and the haemoglobin (purple and bluish-green) and oxyhaemoglobin in the vascular system. Prostheses are usually coloured using synthetic pigments. When a colour reproduction of a prosthesis is matched against the skin of the patient, the prosthetist attempts to adjust the amount and type of pigments used with the prosthetic base material until what he sees or, the reflectance spectrum, is similar to that of the skin. That is, under the illuminating light source, a colour match would be reached when the same wavelength of light is reflected from both matching surfaces. When different illuminants are used, the same prosthesis and skin surfaces may give a different reflectance spectrum, resulting in metameric colour differences.

Menough (1986) suggested that metamerism can be reduced by colour-matching objects under 3 separate light sources, viz, artificial daylight, white-light and yellow light, all of which are the more common household or office light sources. However, achieving a good match under 3 separate light sources would be too precarious and time consuming. A review of the literature failed to identify any study on metamerism in aesthetic prostheses under different light sources. This is expected as prosthetic developments worldwide have been preponderantly focused on the functional rather than the aesthetic aspects of physical loss.

This study compared the colour differences in multi-layered silicone rubber finger prostheses under 3 reference illuminants. The colour reproduction is based on a fair-skinned individual. The aim was to identify the choice of illuminants for colour matching the prostheses that would give rise to the least metameric effect between the prostheses and the human skin or the best colour match.

Fig 1. The spectrophotometric unit used for assessing the colour match results and the four prostheses which were prepared under illuminant TL84, F, D65 and a combination of TL84-F-D65.

Material and methods

Preparation of sample prostheses

Moulding and prosthesis design: Four (4) finger prostheses (Fig. 1) were made from the same master negative impression mould of the left index finger of the Subject C (NKM). Each prosthesis was moulded with an outer translucent layer and an inner opaque layer of silicone rubber. Colour pigments (Cosmesil, Cosmedica Ltd, UK) were intrinsically mixed into clear liquid silicone elastomer (Cosmesil, Cosmedica Ltd, UK) prior to moulding. A layer of coloured touch-ups between the two layers of silicone was added to impart a life-like appearance to the prosthesis. This technique of colouring prostheses is based on the multiplier anatomy and optical characteristics of the human skin (Leow *et al.*, 1997; Pereira *et al.*, 1996).

Colour-matching and standard light sources: Colour-matching of the prostheses was carried out in a standardised colour-matching/assessment cabinet (Verivide, Leslie Hubbell Ltd., UK) under 3 reference illuminants as standardised by the Commission Internationale de l'Eclairage (CIE). The three reference illuminants used were "TL84" or whitelight (colour temperature of 4400K); "D65" or artificial daylight (colour temperature of 6500K); and "F" or yellow light (colour temperature of 2000K) (also known as CIE illuminant "A"). The assessment cabinet also allowed for simultaneous operation of the 3 illuminants and hence the 4 prostheses were colour-matched under this condition. The illumination levels measured by a Luk-meter for TL84, D65, F and the combined illuminations were 2100, 1540, 1500 and 4880 lux, respectively. The intensity of the ambient light outside the cabinet was recorded at 634 lux.

The same prosthetist (MELL) who has been fabricating and colour-matching custom-made prostheses over the last 10 years, did all colour-matching steps. The colour hue was adjusted by varying the amount and the type of pigments used. The degree of opacity of the silicone layers was controlled by varying the volume of pigments to the base material. For a translucent layer, a density of 0.15ml of pigments per 10g of silicone rubber was used. For an opaque layer, it ranged between 0.5 to 1.0ml of pigments per 10g of silicone rubber.

Table 1. L^*,a^*,b^* values (under D65 light source) and colour formulation of the inner and outer layers of the prostheses. The colour for the outer layer was similar for all 4 prostheses while that for the inner layer varied according to the colourmatch under the given lighting conditions.

Prosthesis	Type of lighting used for colour-matching	Mean (SD) L^*, a^*, b^* values under D65 light source				Colour pigments used to obtain the L^*,a,b^* values (ml / 1kg of silicone rubber)							
		Layer	L^*	a^*	b^*	#1	#2	#3	#4	#5	#6	#7	#8
1	TL84 (White light)	Outer	79.00 (0.04)	9.56 (0.06)	24.71 (0.11)	5	8	2	–	–	–	–	–
		Inner	56.44 (0.37)	12.87 (0.08)	23.06 (0.09)	60	12	5	–	2	–	–	–
2	D65 (Daylight)	Outer	79.00 (0.04)	9.56 (0.06)	24.71 (0.11)	5	8	2	–	–	–	–	–
		Inner	56.81 (0.09)	7.91 (0.07)	25.55 (0.03)	50	–	–	40	6	–	–	–
3	F (Yellow light)	Outer	79.00 (0.04)	9.56 (0.06)	24.71 (0.11)	5	8	2	–	–	–	–	–
		Inner	53.75 (0.13)	20.33 (0.04)	11.47 (0.02)	–	–	–	–	30	31	115	32
4	Combined (TL84-D65-F)	Outer	79.00 (0.04)	9.56 (0.06)	24.71 (0.11)	5	8	2	–	–	–	–	–
		Inner	57.98 (0.11)	12.29 (0.09)	21.18 (0.06)	60	–	4	5	–	–	7	–

Pigment used:
#1 -Basic Medium Brown; #2 –Basic Yellow;
#3 –Master Brown; #4 -Master Yellow;
#5 –Master Blue; #6 –Master Sienna;
#7 –Master White; #8 -Master Red.

The 4 prostheses were colour-matched to Subject C's index finger under different reference illuminants. Extraneous light was excluded during the colour-matching processes. The colour formulation for the inner opaque silicone layer was achieved from previous trials (Leow *et al.*, 1996 and 1997) such that when laminated with the outer translucent layer, the composite colour of the prosthesis matched the left index finger of Subject C. The colour for the outer translucent silicone layer was the same for all 4 prostheses (Table 1).

CIE 1976 (L^*,a^*,b^*) colour standardisation of layers: The colour of the silicone layers was measured and recorded in L^*, a^* and b^* values using a tristimulus colorimeter (Chroma Meter CR-300, Minolta, Tokyo, Japan) under a D65 light source (Fig. 1). This was done to standardise the colour and hue of the layers used in the prostheses (Table 1). Under the CIE, 1976 L^*, a^*, b^* Colour Scales, a colour measurement in the $+a^*$ direction indicates a shift towards red in the spectrum while - a^* measurement indicates that the colour shifts to green in the spectrum (Table 2). A $+b^*$ measurement is a shift towards the yellow end while a - b^* is a shift towards blue. The L^* measurement gives the lightness value of the colour with $L^*=100$ representing purest white $L^*=0$ represents the deepest black.

Assessment of the colour match of sample prostheses

Quantitative spectrophotometer measurement: A spectrophotometer (CM-508d, Minolta, Tokyo, Japan) was used to measure the colour differences of each of the completed prostheses against the index finger of the subject under the 3 reference illuminants. Measurement under the combination of the 3 reference illuminants was not possible with this system and hence was not included in this study. The L^*, a^* and b^* values recorded by the spectrophotometer were based on the reflectance spectrum of the dorsal skin of the digit and by matching the same area on the prosthesis, under the given illuminant. Three readings were taken for each sample, within an area of radius 5 mm. The size of the colour difference, ΔE^*, between the prosthesis and the skin would give an indication of the accuracy of

Table 2. A reference table of the attributes in the differences in the CIE colour co-ordinates.

Difference in CIE colour co-ordinates		Attribute characteristics
ΔL^*	Increase	Darker shade
	Decrease	Lighter shade
Δa^*	Increase	More red
	Decrease	More green
Δb^*	Increase	More yellow
	Decrease	More blue

the colour match. ΔE^* is calculated by the equation:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

where ΔL^*, and Δb^* are the respective differences between the prosthesis and the index finger of the subject. In short the smaller the ΔE^* the better the colour-match.

Visual assessment: A total of 50 observers from various occupational backgrounds participated in the visual assessment of the prostheses. Individuals with a history of a defective colour vision were excluded from the study. All visual observations were made within the colour-matching/assessment cabinet (Verivide, Leslie Hubble Limited, UK). The colour discrimination of the prostheses against the subject's finger was ranked and scored between a scale of 1 to 10 for each of the reference illuminants. Sufficient time was given to allow for the observers to adapt to the light source. Each prosthesis was placed adjacent to the left index finger of the subject during the visual assessment and ranking.

Results

Colour difference measurement under reference illuminants using the spectrophotometer

The L^*, a^* *and* b^* values assessed under the 3 different reference illuminants, on equivalent areas of the dorsal skin of the standard subject's index finger and the 4 prostheses were taken and summarised in Table 3a. The mean CIE colour differences ΔL^*, Δa^*, Δb^* and ΔE^* between the subject index finger and each prosthesis were calculated (Table 3b). An Analysis of Variance (ANOVA, α=0.05) with a Scheffe post-hoc multiple range test was done to test these colour differences in the prostheses prepared and assessed under the 3 reference illuminants.

Prosthesis colour-matched under TL84: The prosthesis prepared under TL84 was measured to have a smaller colour difference under TL84 (ΔE^* = 2.51) and D65 (ΔE^* = 2.53) than F (ΔE^* = 3.69). The Δa^* increased under illuminants D65 and decreased under F. The Δb^* was also higher under F. This means that the prosthesis compared to the skin was measured to be more red under D65 but more greenish-yellowish shade under F.

Table 3a. Mean spectrophotometry L^*, a^*, b^* values measured under the three reference illuminants were taken from an equivalent area on the dorsal side of the finger and the prosthesis.

	Assessed under different illuminants								
	TL84			D65			F		
	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*
Standard - (subject's dorsal skin on the finger)	58.81	14.71	21.78	57.83	10.90	18.26	60.17	17.25	20.39
Prosthesis 1 (TL84)	57.36	12.66	21.80	56.00	12.44	19.09	58.55	14.94	22.77
Prosthesis 2 (D65)	57.77	11.17	21.89	56.42	11.40	19.26	58.87	13.85	22.81
Prosthesis 3 (F)	56.49	15.26	18.56	55.23	14.78	16.11	57.91	17.28	20.28
Prosthesis 4 (TL84-D65-F)	57.80	13.51	21.58	56.38	13.28	18.85	59.03	15.67	22.76

Table 3b. The mean CIE colour determinants differences ΔL^*, Δa^*, Δb^* values of prosthesis prepared under different illuminants compared to an equivalent area on the standard subject's dorsal skin. The mean colour difference, ΔE^*, was calculated based on the assessment done under the three reference illuminants.

	Indices based on assessment under reference illuminants											
	TL84				D65				F			
Prosthesis prepared under different illuminants	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*	ΔE^*
Prosthesis 1 (TL84)	-1.45	-2.05	+0.02	2.51	-1.83	+1.54	+0.83	2.53	-1.62	-2.31	+2.38	3.69
Prosthesis 2 (D65)	-1.04	-3.54	+0.11	3.69	-1.41	+0.50	+1.00	1.80	-1.30	-3.40	+2.42	4.37
Prosthesis 3 (F)	-2.32	+0.55	-3.22	4.01	-2.60	+3.88	-2.15	5.14	-2.26	+0.03	-0.11	2.26
Prosthesis 4 (TL84-D65-F)	-1.01	-1.20	-0.20	1.58	-1.45	+2.38	+0.59	2.58	-1.14	-1.58	+2.37	3.07

Prosthesis colour-matched under D65: The prosthesis prepared under D65, had the lowest overall colour difference when measured under D65 light (ΔE^* = 1.80) as compared to assessment under TL84 (ΔE^* = 3.69) and F (ΔE^* = 4.37). The Δa^* was lower under TL84 but higher under F while the Δb^* was higher under both illuminants TL84 and F, more under F. This means that the prosthesis was measured to have a little greenish shade (Δa^*=-3.54, Δb^*=+0.11) under TL84 with a more greenish-yellowish shade (Δa^*=-3.40, Δb^*=+2.42) under F.

Prosthesis colour-matched under illuminant F: For this prosthesis, the spectrophotometric colour difference was the lowest under F (ΔE^*=2.26) then under TL84 (ΔE^*=4.01) and D65 (ΔE^*=5.14). The prosthesis was measured to have a more reddish-bluish shade (Δa^*=+0.55, Δb^*=-3.22) under TL84 and even more reddish shade (Δa^*=+3.88, Δb^*=-2.15) under the D65.

Prosthesis colour-matched under the combined illuminants of TL84-D65-F: The prosthesis colour-matched under the combined illuminants was best assessed under TL84. In fact, overall, between this prosthesis and the subject's actual finger the ΔE^* was lowest (=1.58) although under D65 the prosthesis was measured to have a more reddish shade (Δa^*=+2.38, Δb^*=+0.59).

Visual assessment of the prosthesis

A summary of the aggregate mean qualitative scores of the prosthesis under 3 reference illuminants and based on visual assessment by 50 observers is shown in Table 4. The prosthesis that was prepared under the combined light source was ranked highest by the observers when assessed under TL84 (aggregate score = 8.28, SD=1.22). The mean scores for the assessment were significantly higher (ANOVA; F=7.75, p=0.001) when the prosthesis was assessed under the same light in which it was prepared.

The mean visual scores were compared against the colour difference, ΔE^* measured by the spectrophotometer (Fig. 2).

Discussion

The common reported causes of colour discrepancy in digital prostheses are due to changes in blood volume arising from changes to the position of the hand, the ambient temperature and to skin tones from sun-tanning. During the 2-month period over which the study was done, the subject made special efforts to maintain minimal outdoor activities so as to reduce the influence of tanning and its effect on the colour of the skin. The authors note that the more significant cause of colour discrepancy resulted from the effect of metamerism (Kovan *et al.*, 1981; Leow *et al.*, 1996). Often patients complain that their prosthesis, which has been well-matched to the colour of their skin under the office light source, would seem to have lost its colour match under natural daylight. This study demonstrates this effect comparing the visual assessment by a random group of observers to colour difference measured by a spectrophotometer.

The authors found that assessment under illuminant F had the skin always appearing to be darker with a more reddish shade, such that the prostheses when matched to the skin under F, would appear more red and blue when assessed under the other light sources, like daylight. Prostheses that were prepared and assessed

Table 4. Summary of the mean (SD) qualitative scores of the visual ranking by the panel of observers (n=50). The observers were asked to rank between 1 and 10, the colour difference between the standard subject's finger and the prosthesis that were prepared under the different reference illuminants.

	Aggregate mean (SD) qualitative score		
Prosthesis prepared under	Visual assessment of prosthesis under the reference illuminants		
	TL84	D65	F
1 (TL84)	8.00 (SD, 1.11) ^{a}	6.20 (SD, 1.74) ^{b}	5.73 (SD, 1.81) ^{b}
2 (D65)	7.03 (SD, 1.58) ^{b}	7.55 (SD, 1.41) ^{b}	2.93 (SD, 1.85) ^{c}
3 (F)	5.90 (SD, 1.57) ^{b}	5.53 (SD, 1.41) ^{b}	8.05 (SD, 1.18) ^{a}
4 (TL84-D65-F)	8.28 (SD, 1.22) ^{a}	7.33 (SD, 1.58) ^{b}	6.05 (SD, 1.41) ^{b}

The superscript indicates the homogenous subsets (a-c) from a Scheffe post-hoc multiple range test based on a ANOVA, F=39.472, p<0.001.

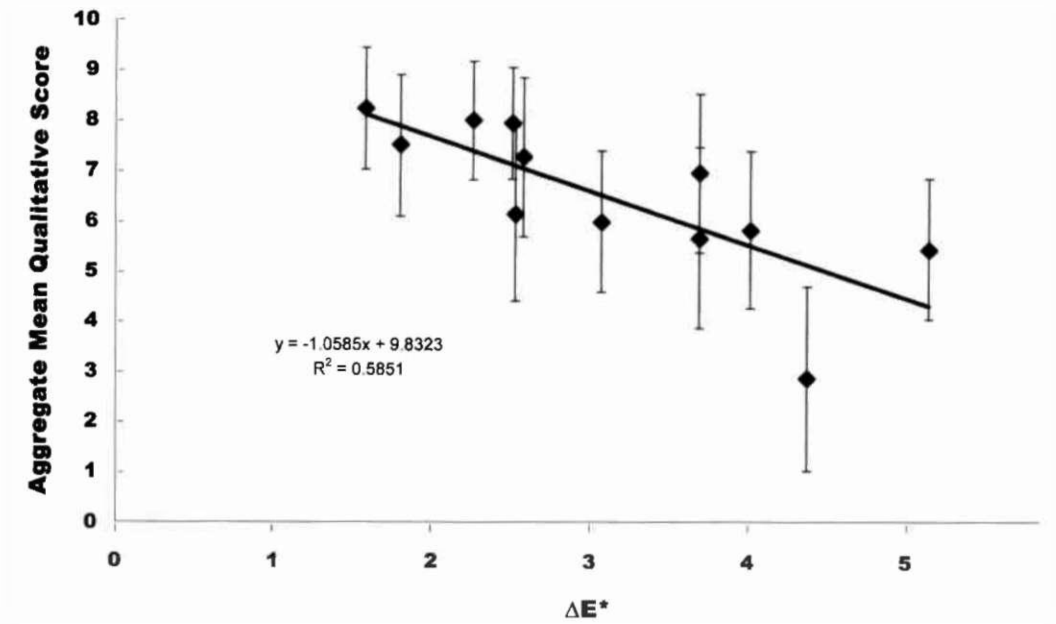

Fig 2. The prosthesis colour matched to the standard subject's index finger under TL84, D65, F and the combination of TL84-D65-F, was assessed by a panel of observers. The visual assessment was scored between 1 to 10 for its colourmatch and measured for its colour difference with a spectrophotometer using the CIE index of L^*, a^*, b^*. Assessment of the prosthesis against the finger was done under 3 reference illuminants – TL84, D65 and F. This graph shows the relationship between the aggregate mean qualitative score from the visual assessment against the CIE colour difference index, ΔE.

under the same light source as compared to assessment under different light sources were found to have a lower ΔE. (The ΔE^* were 1.80 for D65, 2.26 for F and 2.51 for TL84, in ascending order). However, the lowest ΔE value was the prosthesis that was matched under combined light and assessed under illuminant TL84 ($\Delta E^* = 1.58$).

The authors were not able to quantitatively measure the colour-match under the combined light source, but the findings suggest that a prosthesis prepared under a combined light source appeared to have the best match. Both the spectrophotometric and the qualitative assessment by the panel, indicated that the prosthesis prepared under a combined light gave the best results when assessed under illuminant TL84.

The results of this study may be specific to the pigments used in this study and cannot be generalised for other prosthetic pigments. This paper simply points out the concerns related to the optical phenomenon of metamerism with the colour pigments used (Cosmesil™) which can affect the colour match of the prosthesis as perceived by the patient. The findings seem to suggest that this metameric colour difference can be minimised if the prosthesis is matched under a combination of lights, which were found to give the best perceived match.

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