Eur. J. Prosthodont. Rest. Dent., Vol.19, No. 4, pp 168-174
Printed in Great Britain

doi:10.1922/EJPRD_1003Jarad07

Performance Assessment of Vita Easy Shade Spectrophotometer on Colour Measurement of Aesthetic Dental Materials

N. ALGhazali* , G. Burnside†, P.W. Smith‡, A.J. Preston§ and F.D. Jarad¶

Abstract - *Four different shades were used to produce 20 samples of resin-based composite and 20 samples of porcelain to evaluate the performance ability of an intra oral test spectrophotometer compared to a reference spectrophotometer. The absolute colour coordinates CIELAB values measured with both spectrophotometers were significantly different ($p<0.001$). However, a high correlation was found ($p<0.001$) despite the low concordance noticed. The colour difference ΔE* values calculated between different shades also were significantly different between both spectrophotometers ($p< 0.05$). Therefore, the Easy Shade can be used in dental practice and dental research with some limitations.*

KEYWORDS: performance, spectrophotometer, composite, porcelain, colour, colour difference.

INTRODUCTION

One of the aims of restorative dentistry is to restore missing tooth structure to its natural shape, function and appearance. Reproducing the appearance of natural teeth is a challenging process which requires a careful construction of the aesthetic restoration in terms of shape, surface texture, colour and translucency. However, it seems that a significant proportion of the problems associated with aesthetic restorations are those related to colour matching procedures [1].

The increased demand for aesthetic dental restorations has raised the importance of reliable colour reproduction procedures. Appropriate selection of shade and replicating that shade is considered as the most essential step required for achieving a good colour match between a restoration and natural teeth. This in turn, is considered to be highly dependent on the ability to determine tooth colour in a consistent and precise way [2]. The most traditional way used for colour determination is via the use of shade guides. However, shade guides serve as an intermediate tool and therefore two main sources of error are produced; one is in shade determination by a clinician and the other, in shade reproduction by a technician [3].

The colour of an object is a visual perception of the visible light that it reflects and/or transmits [2]. Visual assessment of tooth colour is considered greatly subjective and inconsistent due to several variables which can be either an external variables such as light conditions, or an internal variables such as experience, age, fatigue of human eye [4,5], and other physiological factors such as colour vision confusion (CVC), often called colour blindness [6]. Moreover, standardisation of verbal means for visual colour determination is limited [1].

In spite of these limitations, the human eye can detect even small colour differences between two substances.

The problems and short-comings related to visual colour assessment may be overcome by using objective metric techniques. Several colour-measuring instruments have been developed for colour measurement under standardised conditions [7]. These instruments can be spectrophotometers, colorimeters, or digital cameras.

Several studies have evaluated different colour-measuring instruments and compared the colour determination accuracy of such devices to that of human observers. In Paul's study [5]; it was revealed that the spectrophotometric colour determination and communication can be used effectively for producing of metal ceramic restorations. Crowns produced with a spectrophotometric assessment have a considerably better colour match and lower rate of rejection due to shade mismatch in comparing to crowns produced by using a conventional shade matching process [8]. Additionally, it has been found that the spectrophotometric shade assessment is more accurate and more reliable compared with human shade determination [5].

A spectrophotometer is measuring the spectral reflectance or transmittance curve of an object. Light is released from a light source in the spectrophotometer and then dispersed by a prism into a spectrum of different wavelengths between 380-780 nm. The spectrophotometer then measure the amount of the light reflected from the specimen for each wavelength in the visible light, and convert the data into numerical values of colour coordinates CIE L*, a* and b* [9].

The ability to measure colour of natural teeth and aesthetic restorations reliably and accurately is the most important consideration for selecting a colour-measuring instrument. Reproducibility and precision indicate the consistency of the instrument in matching the same object, and can be assessed by comparing repeated measurements of the same sample or standard. The accuracy of a colour-measuring instrument indicates the ability of this instrument to pro-

† PhD
‡ BDS, MDS, PhD, FDS, DRD, MRD, FDS(Rest Dent), RCS (Edin), ILTM
§ BDS PhD FDS FDS(Rest Dent) RCS (Eng) ILTHE
¶ BDS, PhD, MFDS RCS(Eng), MRD RCS (Edin) Endodontics, FHEA

duce a correct match for a given sample. This can be evaluated by comparing a test instrument to a reference one which is considered to be correct [3]. The accuracy of a colour-measuring instrument (test instrument) are evaluated by two means; firstly by comparing absolute colour coordinates L*, a* and b* values for all samples measured with the test instruments to those values made with the reference instrument and this is called absolute accuracy; secondly, by comparing the colour difference values calculated between different samples using the test instruments to those values made with the reference instrument and this is called relative accuracy [1].

Moreover, colour perception depends on psych-physiological responses to the light, and it might differ from one observer to another, thus, it is appropriate to assess the accuracy of a colour-measuring instrument as well by evaluating the degree of concordance of its measurements to the measurements obtained with a widely-used reference machine [10].

Two types of errors influence colour measuring process using a colour-measuring instrument: systematic errors and random errors. Random errors, which tend to influence the precision and reliability of the instrument, including instrument drift, background noise, polarisation and preparation of the samples. On the other hand, systematic errors including inaccurate calibration, wavelength, filter design, detector sensitivity and linearity, fluorescence, and varied geometries of colour measurements tend to influence the accuracy of the instrument [11].

Different commercially available colour measuring instruments were evaluated and different levels of accuracy were noticed. The Easy Shade spectrophotometer was more precise and accurate than colorimeters (IdentaColor II, and ShadeEye) and digital cameras (ShadeScan and Ikam) been evaluated [12]. Moreover, it has been revealed that the Easy shade spectrophotometer was the most accurate instrument comparing to the other instruments used (Spectroshade (Spectrophotometer), ShadeVision, and ShadeScan (Digital Cameras) [3]. However, none of these studies have evaluated the accuracy of this colour-measuring instrument (Easy Shade spectrophotometer) by comparing its colour measurements to those obtained by a reference machine.

Aim of the study

The aim of this study was to evaluate the performance ability of intra oral test spectrophotometer compared to a reference spectrophotometer.

Four null hypotheses were devised for this study:

1- There is no difference in colour coordinates (L*, a*, and b*) values for resin-based composite and porcelain materials measured by test or reference spectrophotometers (absolute accuracy).

2- There is no difference in ΔE* values calculated between different shades of resin-based composite and porcelain when using test or reference spectrophotometers (relative accuracy).

3- There is no correlation between colour coordinates (L*, a*, and b*) values of resin-based composite and porcelain measured by test or reference spectrophotometers.

4- The test spectrophotometer used is not a precise instrument.

MATERIALS AND METHODS

Study design:

Four different shades were used to produce 20 samples of commercially available resin-based composite and 20 samples of porcelain (five samples for each shade). CIE L*, a* and b* coordinates for all samples were measured using an intra oral test spectrophotometer (Easy Shade spectrophotometer) and a reference spectrophotometer (Minolta CM-2600d). Colour difference ΔE* values were calculated between different shades within each material. The colour coordinates L*, a* and b* values and the colour difference ΔE* values obtained by both spectrophotometers were then compared.

Sample fabrication

Four different shades (A1, A2, A3, and A3.5) of both resin-based composite Filtek Z250 and dental porcelain Omega 900 were used to fabricate discs of 2.1 mm thickness and 13 mm diameter by using a mould made of polyvinyl siloxane putty silicone (Figure 1). Five samples were produced for each shade (20 samples in total).

Resin-based composite was packed into the silicone mould. Samples were light cured at five different sites from both sides each for 20 seconds (Curing light XL3000).

The porcelain powder (Omega 900) and modelling fluid were mixed and packed with vibration into the silicone mould. Excess moisture was removed using paper tissue to minimize porosity of the samples. Then the condensed samples were placed on a suitable tray and fired in a vacuum furnace at a temperature of (950 °C) according to the manufacturer instructions.

Resin-based composite and porcelain discs were then ground to ± 0.05mm of the prescribed thicknesses 2 mm and polished using 150-, 1000-, 1500-grit silicon carbide papers (Rhynowet Plus) with running water. The thickness of the samples was determined using a digital thickness scale (Mitutoyo).

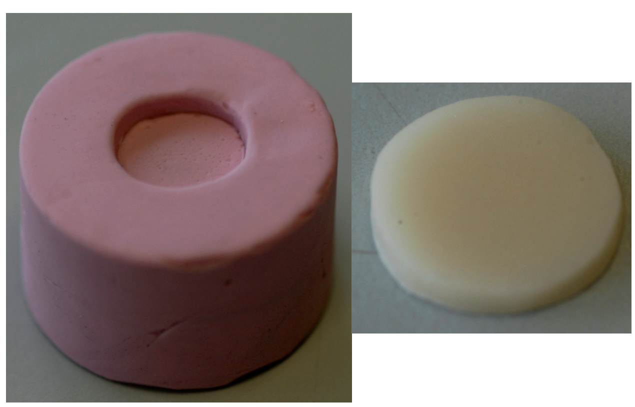

Figure 1. *The putty silicone mould used to fabricate samples and a resin-based composite disc.*

Colour-measuring devices

Two different colour-measuring instruments were used in this study:

The Easy Shade spectrophotometer (Vita Easy Shade) which calculates CIELAB values for 2° observation and D65 illumination curve. This instrument uses hand hold probe with 5 mm measurement area and emits light using one halogen lamp.

The single tooth measurement mode was selected to measure the samples. Calibration was performed by placing the probe tip on the calibration port built in the machine (one standard for calibration) before each specimen measurement; and each specimen was measured by holding the probe tip (5mm diameter) at 90 degrees to the surface in the middle of the disc (Figure 2).

The reference spectrophotometer (Minolta CM-2600d) which has an integrating sphere system which uses (d/8) diffuse illumination and 8-degrees viewing geometry. An integrating sphere is a spherical apparatus with its internal surface covered with a white substance such as barium sulphate, so the light is uniformly diffused in all directions.

Figure 2. *Vita Easy Shade spectrophotometer.*

Figure 3. *Minolta CM2600d, Minolta Konica spectrophotometer.*

The Minolta spectrophotometer was used in an almost similar setting to that used with Easy Shade as follows: D65 illumination curve; 2° observation angle; specular component excluded (SCE) as it is already excluded in Easy Shade spectrophotometer; ultraviolet light (UV) included since the D65 illumination used in Easy Shade states the average daylight including ultra violet wavelength region; and small aperture size (SAV) of 3mm/6mm measurement area since the probe tip of Easy Shade is of 5mm measurement area.

Calibrations were performed as per the manufacturer instructions using two different standards: the zero calibrations and the white calibration (Figure 3).

The colour measurements were standardised by using same black background, one operator, and same lighting conditions. Three measurements for each sample was taken and the means (L*, a*, and b*) were recorded.

Ten randomly selected samples (5 samples from each resin-based composite and porcelain materials) were measured again in the same day.

The accuracy of the test spectrophotometer was evaluated in terms of absolute accuracy, relative accuracy, correlation and concordance.

The precision of the test spectrophotometer was also evaluated in terms of the consistency of its repeated measurements.

The absolute accuracy of a colour measuring device is the ability to perfectly achieve the absolute colour coordinates L*, a* and b* measurements of individual sample. This was assessed by statistically comparing the absolute colour coordinates of each resin-based composite and porcelain sample obtained with the test instrument and the corresponding colour coordinates obtained with the reference instrument using a paired t-test. Moreover, absolute colour difference ΔE* values were calculated using the following formula [13]:

$$\Delta E^*_{Rt} = ((L^*_R - L^*_t)^2 + (a^*_R - a^*_t)^2 + (b^*_R - b^*_t)^2)^{1/2}$$

where L^*_R, a^*_R, and b^*_R express the values determined using the reference machine (Minolta), and L^*_t , a^*_t , and b^*_t express the values determined using the test machine (Easy shade).

The relative accuracy of a colour measuring device is the ability to correctly determine the colour difference values between two different samples. This was evaluated by statistically comparing the colour difference values calculated between each possible paired combination of the four shades within porcelain and resin-based composite groups obtained with the test spectrophotometer and the corresponding colour difference values obtained using the reference spectrophotometer using a paired t-test.

Colour difference values (ΔE_{ab}*) between each possible paired combination of the four shades of both porcelain and resin-based composite materials were calculated using the following formula

$$\Delta E^*_{ab} = \sqrt{(L_a{*} - L_b{*})^2 + (a_a{*} - a_b{*})^2 + (b_a{*} - b_b{*})^2}$$

Where L_a*, a_a*, and b_a* are the mean colour coordinates for one shade obtained with the test spectrophotometer, and L_b*, a_b*, and b_b* are the mean colour coordinates of another shade obtained with the same spectrophotometer.

Therefore, the relative accuracy were assessed by comparing $\Delta E^*_{ab/1}$ and $\Delta E^*ab_{/2}$ where $\Delta E^*_{ab/1}$ was the colour difference values between different shades obtained with the test spectrophotometer, and $\Delta E^*_{ab/2}$ was the corresponding colour difference values obtained using the reference spectrophotometer.

Correlation and Concordance

The absolute colour coordinates L*, a* and b* measurements for all samples within resin-based composite and porcelain groups obtained with the test instrument and those obtained with the reference instrument were tested for correlation using Pearson's correlation coefficient, and for concordance using Lin's concordance coefficient [14]. Moreover, linear regression was conducted to determine the formula parameters that may express the relation between colour measurements made with these two spectrophotometers.

Precision (reproducibility)

The absolute colour coordinates L*, a* and b* measurements of the ten randomly selected samples were compared to those measurements made at the same day using Lin's concordance coefficient [14].

RESULTS

Absolute accuracy

The absolute colour coordinates L*, a* and b* values measured with the test spectrophotometer and those measured with the reference spectrophotometer were significantly different for both resin-based composite and porcelain materials ($p<0.001$). The results based on paired samples t-test are illustrated in Table 1. The absolute colour difference values (calculated between the absolute colour coordinates L*, a* and b* values measured with the test spectrophotometer and those measured with the reference spectrophotometer) were $\Delta E_{RT}^*=13.95$ (13.4-14.5 at 95% Confidence Interval) for resin-based composite and $\Delta E_{RT}^*=14.7$ (14-15.4 at 95% Confidence Interval) for porcelain.

Relative accuracy

The colour difference values calculated between each pair shades using the test spectrophotometer were significantly different from those colour difference values calculated between the corresponding pair shades using the reference spectrophotometer for both resin-based composite and porcelain ($p< 0.05$). Results based on paired samples t-test are shown in Table 2.

Correlation and Concorda

Significantly high correlations were found between all CIELAB colour coordinates measured with the test spectrophotometer and those measured with the reference spectrophotometer at p-value <0.001. The Pearson's correlation coefficients were illustrated in Table 3. However, low concordance coefficients were found (Table 3).

The formula used to determine the relation between colour coordinates CIELAB measured with both spectrophotometers is: Y= a X+ b where the Y is the predicted colour measurement of the reference spectrophotometer, X is the real colour measurement made with the test spectrophotometer, a is the slope and b is the intercept. The slopes and intercepts for each colour coordinate L*, a* and b* was determined using the linear regression test, and they are listed in Table 4.

Precision

Very high concordance was noticed between repeated colour measurements made with the test spectrophotometer at the same day for both resin-based composites and porcelain materials ($p<0.001$). Lin's concordance coefficients were (0.999, 0.996 and 1.0) for L*, a* and b* coordinates respectively.

DISCUSSION

The first null hypotheses was rejected since the absolute colour coordinate L*, a* and b* values measured with the test instrument was statistically different from those measured with the reference instrument for both resin-based composite and dental porcelain samples ($p<0.001$). The absolute colour difference ΔE_{RT}* values calculated between absolute colour coordinates measured with the test and reference instruments were 13.95 for resin-based composite and 14.7 for porcelain, which are highly above the 1 ΔE* unit presented as a perceptibility threshold [15] and 5.5 ΔE* units presented as an acceptability threshold in clinical conditions [16].

These significant differences may be explained by a number of variables that can affect the absolute accuracy of the test spectrophotometer. Measuring the colour of a sample using the test spectrophotometer is accomplished by holding the probe tip at 90 degrees to the sample surface. Therefore, any minor angulations of the probe might cause an edge-loss effect. In this effect, the illuminating beam is scattered within the specimen beyond the edge of the probe tip especially when measuring translucent samples [17,18,19]. In this study, the edge-loss effect caused by using such probe spectrophotometer with translucent samples of resin-based composite and porcelain materials may result in some inaccuracy of the test spectrophotometer in absolute colour measurements compared to the reference instrument which uses an integrated sphere to illuminate the samples.

Using more than one known standard to calibrate a colour-measuring instrument will give the possibility that the standards may have a varied translucency from the sample and therefore, reduce the errors associated with colour measurements of samples of different translucencies [20]. Unlike the reference spectrophotometer which has two different standards for calibration, the test spectrophotometer is calibrated using just one standard, which might not be sufficient for assure the accuracy of absolute colour measurement of different shades of resin-based composite and porcelain materials.

Table 1. *Significance p values based on paired t-test for the differences in absolute colour coordinates measured with Easy Shade and Minolta spectrophotometers.*

Absolute accuracy	Composite				Porcelain			
	Mean	95% Confidence Interval		Significance	Mean	95% Confidence Interval		Significance
		Lower	Upper			Lower	Upper	
L*	9.8	9.51	10.1	0.000	7.32	6.45	8.19	0.000
a*	1.46	1.59	1.33	0.000	1.31	0.9	1.72	0.000
b*	9.65	8.69	10.62	0.000	12.21	10.7	13.72	0.000

Table 2. *Significance p values based on paired t-test for the relative differences between ΔE* values calculated using Minolta spectrophotometer and corresponding ΔE* values obtained using Easy Shade spectrophotometer.*

Relative accuracy	Mean difference	Std. Deviation	95% Confidence Interval		Significance
			Lower	Upper	
Composite	2.84	1.76	0.99	4.68	0.011
Porcelain	4.89	3.65	1.06	8.71	0.022

Table 3. *Displays the Pearson's correlation coefficient and Lin's concordance coefficient for absolute colour coordinates CIELAB measurements of both resin-based composites and porcelain materials.*

	Composite		Porcelain	
	Pearson's correlation coefficient	Lin's concordance coefficient	Pearson's correlation coefficient	Lin's concordance coefficient
L*	0.961	0.005	0.955	0.267
a*	0.976	0.222	0.974	0.385
b*	0.993	0.158	0.996	0.26

Table 4. *Slopes and Intercepts based on linear regression test for each of the three colour coordinates CIELAB for both resin-based composite and porcelain materials.*

	L*		a*		b*	
	Slope	Intercept	Slope	Intercept	Slope	Intercept
Resin-based composite	0.743	-0.687	0.569	-0.392	0.335	1.464
Dental Porcelain	0.756	1.305	0.453	18.094	0.540	-1.186

Other variables might have influenced the absolute accuracy of the test spectrophotometer compared to the reference instrument including: the spectral resolution is 25nm in the test instrument, while it is 10nm in the reference instrument which produce more accurate measurements; and one tungsten lamp used as an illuminant in Easy shade, while the three pulsed xenon lamps used in Minolta can automatically compensate for any drifting in the intensity of the illumination and result in more accurate measurements [20].

The final assessment in any colour evaluation process is always a visual one, and the most useful of colour data values are those that have some relations to visual judgement [1]. Colour difference values are considered important and more practically useful in dentistry than absolute colour measurements, especially when comparing these colour difference values to the practical parameters (perceptible and clinically acceptable thresholds) [21,22].The second null hypothesis was rejected as significant differences were found between colour difference values determined using the test spectrophotometer and corresponding colour difference values obtained with the reference spectrophotometer ($p<0.05$). The mean differences were 2.84 and 3.65 for resin-based composite and dental porcelain materials respectively which are considerably perceptible. The same mentioned variables may have also influenced the relative accuracy of the test instrument in determining the colour difference values between different shades.

The third null hypothesis was rejected and significantly high correlations were found between both the test and the reference instruments in determining the absolute colour coordinates CIELAB values ($p<0.001$). However, low concordance coefficients were found between them, showing that the two spectrophotometers have given different but correlated measurements. That, in turn, reflects the standard relation between the absolute colour coordinates measurements obtained with both spectrophotometers.

Based on linear regression model, for e.g, colour coordinates L*, a* and b* values of the 5th sample of A3.5 shade of resin-based composite were respectively (67.87, -2.4 and 22.73) when using the test spectrophotometer. The predicted values of the references spectrophotometer using the formula (Y= a X+ b) will be respectively (58.8, -1.09 and 9.88), which are quite close to the real values measured using this references spectrophotometer (58.84, -1.27 and 9.91 respectively). However, the small sample size (20 sample for each material) and the small variety of shades (4 shades of each material) used in this study forms a limitations from using this formula in general, and therefore, more studies are recommended.

The fourth null hypothesis were also rejected and significantly high precision of the test spectrophotometer was noticed in repeated measurements ($p<0.001$), which means that this test spectrophotometer is significantly reliable in colour measurements of both resin-based composites and porcelain materials. This might be explained by the fact that the drifting might happened in this test instrument were very low as calibration of the instrument was performed before each single colour measurement.

Within the limitations of this study, the ability of the Easy Shade spectrophotometer in determining the absolute colour coordinates L*, a* and b* values was not accurate (absolute accuracy) and therefore it is not recommended to be used in studies where the absolute colour coordinates of samples are important to be evaluated (for instance, studies investigating the lightness, hue and chroma of different shades of a dental material).

However, high correlation was found between both test and reference spectrophotometers in determination of absolute colour coordinate values. Additionally, the reliability (precision) of the test spectrophotometer was found to be excellent. Moreover, the test spectrophotometer was the most accurate instrument comparing to other instruments used in production a correct shade of a selected sample [3]. Therefore, the test spectrophotometer can be used for shade reproduction process and in studies evaluating colour shifts or changes, in addition to the advantage of using it intra orally.

Of more practical use, the ability of the test spectrophotometer in determining the colour difference ΔE_{ab}^* values between different shades was not as accurate as the references spectrophotometer. This shortcoming can be overcome by establishing the perceptibility and clinically acceptable thresholds related to the test spectrophotometer. Therefore, further studies in determining such thresholds for the test spectrophotometer and for each individual colour measuring instrument available to use in dental field are recommended.

CONCLUSION

The Easy shade spectrophotometer is considered of limited accuracy in measuring absolute colour coordinates CIELAB in comparing to the reference instrument. However, despite the low concordance, the high correlation between colour measurements obtained with both spectrophotometers means that the Easy Shade can be used in dental practice and dental research with some limitations. Colour difference ΔE_{ab}^* values determined using Easy shade were different from those obtained using the reference instrument, however, this can be overcome by establishing the perceptibility and acceptability thresholds related to each instrument. Easy Shade spectrophotometer is a reliable precise instrument in colour measurements of resin-based composites and porcelain materials.

MANUFACTURERS' DETAILS

- Filtek Z250, 3M ESPE, USA
- Omega 900, Vita, Germany
- Curing light XL3000, 3M ESPE, USA
- Modelling fluid, Vita, Germany
- Rhynowet Plus, Portugal
- Mitutoyo, Japan
- Vita Easy Shade, Vita, Germany
- Minolta CM-2600d, Konica Minolta, Japan

ACKNOWLEDGMENT

Nabiel ALGhazali is funded by Syrian Government, University of Aleppo.

ADDRESS FOR CORRESPONDENCE

Dr Fadi Jarad, Lecturer/Honorary Specialist Registrar in Restorative Dentistry, Liverpool University Dental Hospital, Pembroke Place Liverpool, L3 5PS. Email: fjarad@liverpool.ac.uk

REFERENCES

1. Seghi RR, Johnston WM and O'Brien WJ, Performance assessment of colorimetric devices on dental porcelains, *J Dent Res* 1989; **68**: 1755–1759.
2. Rosenstiel SF, Land MF and Fujimoto J, *Contemporary fixed prosthodontics*. 4th ed., Elsevier, St. Louis, 2006: 712–725.
3. Kim-Pusateri S, Brewer JD, Davis EL and Wee AG, Reliability and accuracy of four dental shade-matching devices, *J Prosthet Dent* 2009; **101**: 193-199.
4. Wyszecki G, Stiles WS, *Color science concepts and methods, quantitative data and formulae*, 2nd ed., New York: Wiley: 1982: 83-116.
5. Paul SJ, Peter A, Rodoni L and Pietrobon N, Conventional visual vs spectrophotometric shade taking for porcelain-fused-to-metal crowns: a clinical comparison, *Int J Peridont Rest Dent* 2004; **24**: 222-31.
6. Carsten DL, Successful shade matching-what does it take, *Compend Contin Educ Dent* 2003; **24**: 175-8.
7. Ratzmann A, Klinke T, Schwahn C, Treichel A and Gedrange T, Reproducibility of electronic tooth colour measurements, *Biomed Tech* 2008; **53**: 259-263.
8. Da Silva JD, Park SE, Weber HP and Ishikawa S, Clinical performance of a newly developed spectrophotometric system on tooth colour reproduction, *J Prosthet Dent* 2008; **99**: 361-8.
9. Berns RS, Billmeyer and Saltzmam's, *principles of colour technology*, 3rd ed., John Wiley & Sons, New York, 2000: 88-92.
10. Billmeyer FW, Comparative performance of color-measuring instruments, *Appl Optics* 1969; **8**: 755-783.
11. Berns RS and Petersen KH, Empirical Modelling of Systematic Spectrophotometer Errors, *Color Res Appl* 1988; **13**: 243-256.
12. Dozic A, Kleverlaan CJ, EL-Zohairy A, Feilzer AJ and Khashayar G, Performance of five commercially available tooth color-measuring devices, *J Prosthodont* 2007; **16**: 93-100.
13. Commission Internationale de l'Eclairage (CIE), *Recommendations on uniform colour spaces, colour-difference equations, and psychometric colour terms*. Supplement No. 2 of publication CIE No. 15 (E-1.3.1) ed, Bureau Central de la CIE, Paris, 1978.
14. Kuei Lin L, A concordance correlation coefficient to evaluate reproducibility, *Int Biometric Soc* 1989; **45**: 255-268.
15. Kuehni RG and Marcus RT, An Experiment in Visual Scaling of Small Colour Differences, *Colour Res Appl* 1979; **4**:83-91.

16. Douglas RD, Steinhaurer TJ, and Wee AG, Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch, *J Prosthet Dent* 2007; **97**: 200-8.
17. Bolt RA, ten Bosch JJ and Coops JC, Influence of window size in small-window color measurement, particularly of teeth, *Physic Med Bio* 1994; **39**: 1133–1142.
18. van der Burgt TP, ten Bosch JJ, Borsboom PC and Kortsmit WJ, A comparison of new and conventional methods for quantification of tooth color, *J Prosthet Dent* 1990; **63**: 155–162
19. Ten Bosch JJ and Coops JC, Tooth color and reflectance as related to light scattering and enamel hardness, *J Dent Res* 1995; **74**: 374–380.
20. Johnston WM, Colour measurement in dentistry, *J Dent* 2009; **37**: e2-e6.
21. Billmeyer and Saltzman's, *Principles of color technology*, 2rd ed., New York: John Wiley & Sons, 1981: 67-110.
22. Judd DB and Wyszecki G, *Colour in business, science and industry*, 3rd ed., New York, John Wiley & Sons, 1975: 91-219.