Reliability and Accuracy of Crystaleye Spectrophotometric System

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Objective: *To develop an* in vitro *shade-measuring model to evaluate the reliability and accuracy of the Crystaleye spectrophotometric system, a newly developed spectrophotometer.*
Methods: *Four shade guides, VITA Classical, VITA 3D-Master, Chromascop and Vintage Halo NCC, were measured with the Crystaleye spectrophotometer in a standardised model, ten times for 107 shade tabs. The shade-matching results and the CIE L*a*b* values of the cervical, body and incisal regions for each measurement were automatically analysed using the supporting software. Reliability and accuracy were calculated for each shade tab both in percentage and in colour difference (ΔE). Difference was analysed by one-way ANOVA in the cervical, body and incisal regions.*
Results: *Range of reliability was 88.81% to 98.97% and 0.13 to 0.24 ΔE units, and that of accuracy was 44.05% to 91.25% and 1.03 to 1.89 ΔE units. Significant differences in reliability and accuracy were found between the body region and the cervical and incisal regions. Comparisons made among regions and shade guides revealed that evaluation in ΔE was prone to disclose the differences.*
Conclusion: *Measurements with the Crystaleye spectrophotometer had similar, high reliability in different shade guides and regions, indicating predictable repeated measurements. Accuracy in the body region was high and less variable compared with the cervical and incisal regions.*

Key words: *colour analysis, colour measurement, shade guide, shade selection, spectrophotometric system*

An aesthetically pleasing restoration should mimic the optical properties of its proximal teeth[1]. Accurate shade selection is the first step to achieve this goal. There are three kinds of shade selection technique, including visual shade selection with shade guides, instrument-based shade selection and digital image analysis. Visual shade selection has been demonstrated to be a subjective process affected by many factors[2-8]. Although a number of shade guide systems are available for clinical use, limitations are found, such as they do not cover the whole spectrum of colour found in natural teeth[9,10], and they are not uniform in colour space[1,11]. In addition, the complex nature of tooth colour and translucency complicates the process of visual shade selection, leading to inconsistencies and bias between and within individuals[7,12,13].

Digital photography has been a popular method to convey colour information to dental laboratories[14,15]. Colour information received from digital cameras is device-dependent, and the quality of the image is also influenced by a number of variables such as lighting conditions, resolution and calibration protocols. Additionally, the camera's sensor, body, lenses, focal length, selected F-stop, and white balance can affect the colour accuracy[16,17]. Usually, digital photography is taken as reference to provide colour, translucency, texture and other optical information of the tooth[18,19].

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Fig 1 Shofu gingival matrix. Shade tabs were fixed in the middle.

Instrument-based shade selection has the potential to eliminate the subjective aspects of visual colour assessment[7,20-22]. Colour-measuring instruments can be divided into two groups, namely colorimeters and spectrophotometers. Spectrophotometers are able to measure the amount of light reflected from objects over the full spectral wavelength[21]. According to the measuring area, spectrophotometers can be subdivided into spot measurement (SM) spectrophotometers and complete-tooth measurement (CTM) spectrophotometers[23]. SM spectrophotometers measure a small area on the tooth surface and several measurements should be performed if the entire tooth colour information is needed[13,24]. CTM spectrophotometers provide colour information of the entire tooth, and the tooth colour map can then be produced by the supporting software. Its image capture also provides a visual image of the target tooth. Therefore, CTM spectrophotometers should provide systematic and accurate measurements and improve the communication with the dental laboratory[25].

The newly developed Crystaleye spectrophotometer (Olympus, Tokyo, Japan) is a CTM spectrophotometer which combines spectrophotometry with digital imaging. It consists of a handheld spectrophotometer and a cradle with a reference plate for calibration. This spectrophotometer uses seven LEDs (light-emitting diodes) as illuminant with 45/0-degree geometry. It can capture the image of a single tooth, the dentition and even the face of the patient. The captured image and the spectral data can be transferred to a personal computer and analysed using the supporting software (Crystaleye Application v.1.4, Olympus). The database of the Crystaleye software system supports the following shade guides: VITA Classical (VITA, Bad Säckingen, Germany), VITA 3D-Master (VITA), Chromascop (Ivoclar Vivadent, Schaan, Liechtenstein), Vintage Halo NCC (Shofu, Kyoto, Japan) and Noritake (Noritake, Nagoya-shi, Aichi, Japan; Noritake was included in the database of the supporting software, but was not included in the present study). Clinical performance of this device was investigated previously. Comparing 36 conventionally fabricated crowns with 36 crowns fabricated using the spectrophotometer, the mean value of colour difference (ΔE) between target teeth and crowns

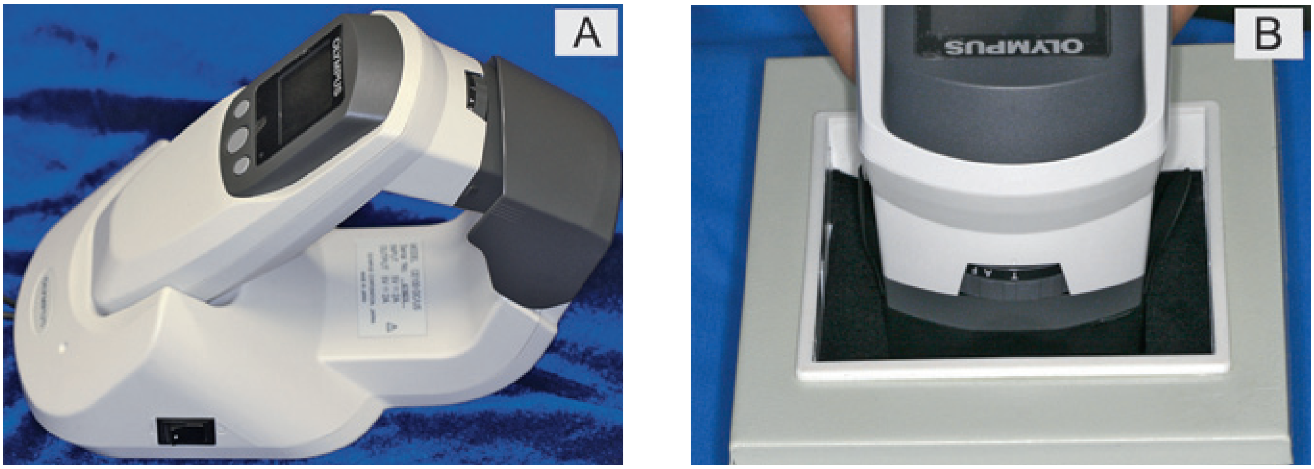

Fig 2 A dental spectrophotometer used in the present study. (A) Scheme of Crystaleye spectrophotometer. (B) Positioning on the black box. A custom holder was placed inside the box.

was significantly lower in the spectrophotometric group in all three tooth regions (cervical, body and incisal)[21]. However, there is lack of *in vitro* evaluations on the reliability and accuracy of this dental spectrophotometer. Reliability and accuracy of other colour-measuring devices have been reported, but they only measured the middle region of the shade tabs, and the incisal and cervical regions were not included[26,27]. As a CTM spectrophotometer, the reliability and accuracy in three regions should be understood. The purpose of the present study is to investigate the reliability and accuracy of the spectrophotometer *in vitro*. The null hypothesis was that there is no difference in reliability and accuracy of the spectrophotometric system when measuring the four shade guides and in different regions of shade tabs.

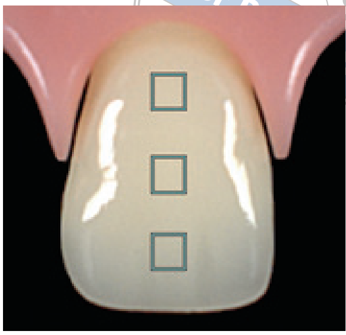

Fig 3 Three areas for colour measurement in cervical, body and incisal regions.

Material and methods

Four shade guides, VITA Classical (16 shade tabs), VITA 3D-Master (29 shade tabs, including 0M1, 0M2 and 0M3 shade tabs), Chromascop (20 shade tabs) and Vintage Halo NCC (42 shade tabs) were tested in the present study. Shofu gingival matrix (Shofu GUMY, Shofu; Fig 1) was used to mimic the surrounding soft tissue of the teeth[26]. A black box (Fig 2) was used to eliminate the influence of external light. An opening was made on the top of the box to hold the spectrophotometer. Every shade tab of the four shade guides was fixed in the middle of a light gingival-coloured matrix, and then attached to a custom holder; the custom holder consisted of two parts, the female part and the male part. The female part was fixed in the black box with a cube-shape slot in the middle; the slot was used to accommodate the male part to which gingival matrix was attached. The holder guaranteed that all shade tabs were positioned in the same location. The black background was attached to the base of the black box. The distance between the shade tab to the tip of the spectrophotometer was about 4 mm and the geometry was 45/0-degree as recommended by the manufacturer. Ten non-consecutive measurements were taken for each shade tab with the spectrophotometer. Prior to each measurement, the spectrophotometer was calibrated according to the manufacturer's recommendation. All measurements were performed by the same prosthodontist who was extensively trained by and calibrated with the instructor of the manufacturer. To ensure the consistency of the measurement, the guide frame displayed on the LCD monitor of the spectrophotometer was referred to during each measurement. The spectral data of each shade tab and the captured images were transferred to a personal computer (ThinkPad X60; Lenovo, Armonk, NY, USA).

Spectral data of each shade tab were automatically analysed with the supporting software (Crystaleye Application v.1.4, Olympus). In the present study, the shade of each shade tab's cervical, body and incisal regions was determined (Fig 3) and the corresponding L*a*b* values were analysed. Reliability was determined by two methods: firstly, it was calculated as the percentage of identical measurements for each shade tab and then averaged for all shade tabs[27]; secondly, each shade tab's CIE L*a*b* values of the ten measurements were averaged, and the colour difference (ΔE) between each measurement and the average value was calculated[24]. To evaluate the accuracy, the percentage of correct-match regions was calculated[26]. The accuracy of the measurement was also evaluated by the colour difference (ΔE) between the measured values and the standard values. The CIE L*a*b* values incorporated in the software were referred to as standard values. Colour difference (ΔE) was determined using the following equations[21,24]:

$$\Delta L^* = L^*_m - L^*_r$$

$$\Delta a^* = a^*_m - a^*_r$$

$$\Delta b^* = b^*_m - b^*_r$$

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

(The subscript m refers to measured value and r means the reference value, that is average value for reliability and standard value for accuracy.)

Reliability and accuracy of the four shade guides were compared by one-way ANOVA and followed by a Bonferroni multiple comparison procedure with SPSS 13 (SPSS, Chicago, IL, USA)[26]. Analysis was performed in cervical, body and incisal regions, respectively. Paired-sample t test was used to analyse the differences in reliability and accuracy between regions. The level of significance was established as $\alpha = 0.05$.

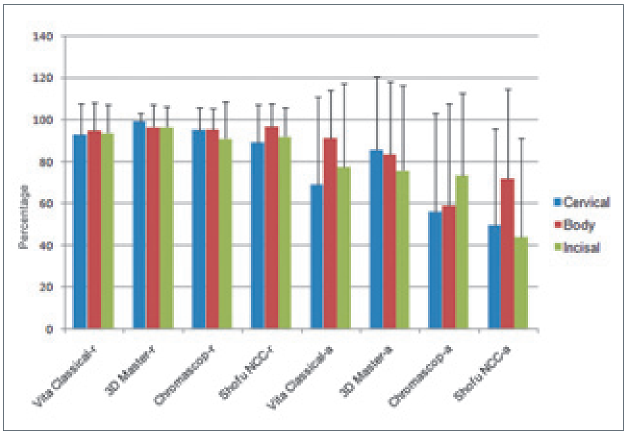

Fig 4 Reliability and accuracy in percentage. -r, reliability; -a, accuracy.

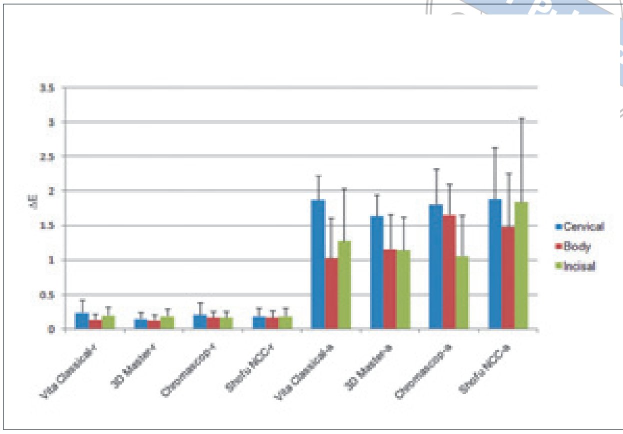

Fig 5 Reliability and accuracy in ΔE units. -r, reliability; -a, accuracy.

Results

A total of 1070 colour measurements were made and 3210 sets of CIE L*a*b* values were obtained by the supporting software.

Mean reliability ranged from 88.81% to 98.97% (Fig 4) and 0.13 to 0.24 in ΔE units (Fig 5). Comparison of reliability in three regions revealed that the body region produced the smallest ΔE values, but when analysed in percentage values no significant differences were observed (Table 1). Multiple comparisons indicated that when analysed in percentage value, there was no significant difference in reliability among the four shade guides. Difference among shade guides in cervical and body regions was obvious in most cases except for the incisal region in ΔE values (Table 2).

Mean accuracy ranged from 44.05% to 91.25% (Fig 4) and 1.06 to 1.89 in ΔE units (Fig 5). Comparison among regions demonstrated that measurement in the body region was most accurate (Table 3). Table 4 shows the differences in accuracy among shade guides in the three regions; when evaluated in ΔE units, 10 of the 18 total comparisons produced a significant difference, but only two in percentage values.

Discussion

For the reliability evaluation, the null hypothesis that the reliability was equal for the four shade guides and in different regions of shade tabs was rejected, for the reliability was quite different between the body and the cervical region ($P < 0.001$) and the incisal region ($P < 0.001$) when calculated in ΔE units. Differences were also seen among shade guides. For the accuracy evaluation, the null hypothesis that the accuracy was equal was also rejected, for differences were observed in different regions and shade guides (Tables 3 and 4).

To evaluate a colour-measuring device, a properly developed protocol is of great importance. The illuminant is a vital factor affecting both visual and instrumental shade selection[3,28]. In the present *in vitro* study, the black box used was able to eliminate the outside light and the custom holder guaranteed that all shade tabs were fixed in the same position of the black box. The advantages of using shade tabs as the colour standard have been reported before[26]. The Shofu gingival matrix was used to mimic the surrounding tissue of natural teeth[26,27]. However, its potential influence on the measurement needs further study. For each measurement, the guide frame was referred to, to control the variance. A previous study demonstrated that small angulations did not affect the accuracy of this spectrophotometer[29]. Therefore, it was reasonably assumed that this model simulated the oral environment and measurements in the model were consistent.

Reliability and accuracy are the most important aspects that should be considered for a colour-measuring device. When the device is reliable, results of the measurement are more predictable. When the device is accurate, it can provide the true colour information of the tooth. In the present study, reliability was evaluated by the percent of identical shade[27] and the variance of CIE L*a*b* values[30]. Reliability in the three regions of the four shade guides ranged between 88.81% to 98.97%, and 0.13 to 0.24 in ΔE units, indicating excellent reliability. Accuracy is defined as the abil-

Table 1 Comparison of reliability in the three regions

	Reliability in percentage		Reliability in ΔE units	
Regions	Difference (SD)	*P*	Difference (SD)	*P*
Cervical vs. body	-2.99 (17.88)	0.086	0.04 (0.12)	<0.001*
Cervical vs. incisal	<0.01 (17.48)	≈1.000	<0.01 (0.14)	0.761
Body vs. incisal	2.99 (17.11)	0.073	-0.04 (0.11)	<0.001*

* significant difference

Table 2 Multiple comparisons of reliability (P)

	Reliability in percentage (*P*)			Reliability in ΔE units (*P*)		
Shade guides	Cervical	Body	Incisal	Cervical	Body	Incisal
VC vs. 3D	0.842	≈1.000	≈.000	<0.001*	≈1.000	≈1.000
VC vs. Chr	≈1.000	≈1.000	≈1.000	0.737	0.531	0.126
VC vs. Shofu	≈1.000	≈1.000	≈1.000	<0.001*	0.003*	≈1.000
3D vs. Chr	≈1.000	≈1.000	≈1.000	<0.001*	0.009*	0.606
3D vs. Shofu	0.020*	≈1.000	0.999	0.003*	<0.001*	≈1.000
Chr vs. Shofu	0.636	≈1.000	≈1.000	0.102	0.590	0.219

* significant difference; Chr, Chromascop; Shofu, Shofu NCC; 3D, VITA 3D-Master; VC, VITA Classical

Table 3 Comparison of accuracy in the three regions

	Accuracy in percentage		Accuracy in ΔE units	
Regions	Difference (SD)	*P*	Difference (SD)	*P*
Cervical vs. body	-12.15 (40.17)	0.002*	0.44 (0.58)	<0.001*
Cervical vs. incisal	0.19 (57.05)	0.973	0.37 (0.92)	<0.001*
Body vs. incisal	12.34 (47.08)	0.008*	-0.07 (0.87)	0.014*

Table 4 Multiple comparisons of accuracy (P)

	Accuracy in percentage (*P*)			Accuracy in ΔE units (*P*)		
Shade guides	Cervical	Body	Incisal	Cervical	Body	Incisal
VC vs. 3D	≈1.000	≈1.000	≈1.000	<0.001*	0.222	0.589
VC vs. Chr	≈1.000	0.101	≈1.000	≈1.000	<0.001*	0.118
VC vs. Shofu	0.790	0.595	0.057	≈1.000	<0.001*	<0.001*
3D vs. Chr	0.121	0.215	≈1.000	0.009*	<0.001*	≈1.000
3D vs. Shofu	0.005*	≈1.000	0.017*	<0.001*	<0.001*	≈1.000
Chr vs. Shofu	≈1.000	≈1.000	0.080	0.595	0.008*	<0.001*

* significant difference; Chr, Chromascop; Shofu, Shofu NCC; 3D, VITA 3D-Master; VC, VITA Classical

ity of the colour-measuring device to provide a correct colour match for a given sample[26], which is the 'correct-matching' ability. It also refers to a measure of how close the measured value is to the 'true' value[24], in other words, the 'close-matching' ability. A wide range in accuracy (49.52% to 85.52% in cervical, 56.00% to 91.25% in body and 44.05% to 77.50% in incisal) demonstrated that the 'correct-matching' ability of this spectrophotometer was influenced by variation among regions and shade guides from different manufacturers. When accuracy was evaluated in terms of colour difference (ΔE), it ranged from 1.03 to 1.89, demonstrating good 'close-matching' ability. Comparisons made among regions and shade guides in reliability and accuracy revealed that evaluation in ΔE was prone to disclose the differences. For thorough evaluation, both the shade-matching results and the CIE L*a*b* values should be investigated, which was not the case in previous studies[26,27].

As a CTM device, the Crystaleye spectrophotometer is able to capture the reflectance spectrum of the entire tooth surface. With the supporting software, the spectral data can be translated into the colour information. Therefore, the shade and the CIE L*a*b* values of the three regions of each shade tab can be analysed. Evaluation of another CTM spectrophotometer demonstrated that the central area of the middle third exhibited the most precise recordings[30]. In the present study, measurements in the three regions were considered reliable in both evaluations, although statistical analysis revealed that the body region was more reliable than the cervical and incisal regions in ΔE units. A similar difference was seen in accuracy evaluation. This could be explained by the fact that the body region has a relatively flat surface: a previous study demonstrated that flattening the measuring surface resulted in a more consistent colour measurement[31]. The curved surface and the surrounding gingival matrix of the cervical region and translucency in the incisal region may influence the reliability and accuracy. Optical properties of the natural teeth are much more complex than shade tabs, and such influences should be further investigated *in vivo*[32].

The perceptibility and acceptability of colour difference between crown and target tooth have been studied previously. Ragain and Johnston[33] reported average acceptability thresholds of 2.72 CIE L*a*b* ΔE units. An early study reported that the average colour difference between compared teeth rated as a match in the oral environment was 3.7 ΔE[34]. Recently, Douglas et al[35] using acrylic resin denture teeth in an intraoral setting indicated that the predicted colour difference at which 50% of the dental practitioner observers could perceive a colour difference (50/50 perceptibility) was 2.6 ΔE units, and the predicted colour difference at which 50% of the subjects would remake the restoration due to colour mismatch (clinically unacceptable colour match) was 5.5 ΔE. A recently reported colour difference between natural teeth and the perfectly matched all-ceramic crowns was 1.6 ΔE[36]. In the present study, the highest average colour difference (1.89 ΔE) in accuracy was not 'perfect', but fell within the acceptable range. The results indicate that differences in accuracy among shade guides and regions may have statistical significance, but can be considered accurate in the 'close-matching' aspect.

The clinical performance of the Crystaleye spectrophotometer has been evaluated previously[21,37]. Crowns fabricated by the spectrophotometer system were superior to those by conventional methods in terms of a lower ΔE value and a significantly higher acceptance/rejection ratio. Because the number of cases was limited and the colour information of each crown was unknown, further clinical and *in vitro* studies are needed. In the present study, four shade guides were used to represent the wide range of tooth colours; the Vintage Halo NCC shade guide has the additional R series of shade tabs, which were considered to represent the tooth colour of the Asian population. To eliminate the potential influence of the inherent difference in shade tabs, only one set of each shade guide was tested. Further study should include the long-term repeatability and interexaminer reproducibility[30].

Conclusions

The model used in this study simulated the oral environment, and measurements in the model were consistent. The *in vitro* study demonstrated that measurements with the Crystaleye spectrophotometer had similar, high reliability in different shade guides and regions, indicating predictable repeated measurements. Accuracy in the body region was high and less variable compared with the cervical and incisal regions. It is suggested that users should recognise the elements that have potential influence on reliability and accuracy of the spectrophotometric measurements and make use of the colour information correctly.

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