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Original article

Clinical evaluation of a dental color analysis system: The Crystaleye Spectrophotometer®

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Abstract

Purpose: To evaluate the clinical performance of the Crystaleye Spectrophotometer®, a dental color analysis system.
Methods: Three color-measuring devices (Crystaleye Spectrophotometer®, CAS-ID1, MSC-2000) were tested and the differences in color measurements among them were evaluated using Scheffe's F-test. Color measurements with the Crystaleye Spectrophotometer® were repeated 10 times by the same operator. The color difference (ΔE) between the first and tenth measurements was calculated. The Crystaleye Spectrophotometer® was used to measure the color of the maxillary left central incisor under two conditions (light and dark) and the effect of exterior lighting was analyzed to assess the accuracy of measurements. Furthermore, five different operators performed color measurements, and ΔE among the three devices was calculated. The ΔE between the target tooth and the crown of a single maxillary central incisor crown fabricated using data from the Crystaleye Spectrophotmeter® was calculated. Color differences between prebleaching and postbleaching were also analyzed with the Crystaleye Spectrophotometer® using the parameters ΔE, ΔL^*, Δa^*, and Δb^*.
Results: The data from the three spectrophotometers were not significantly different. The ΔE during repeated color measurements by the same operator was 0.6. The ΔE between light and dark conditions was 0.9. The data from the five operators were not significantly different. The mean ΔE value between the target tooth and the fabricated crown was 1.2 ± 0.4, and the mean ΔE value between prebleaching and postbleaching was 3.7 ± 1.0.
Conclusions: The Crystaleye Spectrophotometer® is an easy-to-use color analysis system producing accurate color measurements under clinical conditions.

Keywords: Color matching; Instrumental color analysis; Color-measuring devices

1. Introduction

In recent years, esthetic dentistry has become more prevalent because of increasing demand from patients and the development of new techniques and materials that improve the clinician's ability to provide esthetic treatment.

To reproduce a natural tooth color and respond to the expectations of patients, accurate evaluation of the natural tooth color is necessary so that it is reflected in the prosthesis.

Color matching of teeth is recorded through visual shade matching or instrumental color analysis [1]. Visual shade matching is most frequently performed using shade guides. However, commercially available shade guides contain a limited selection of colors when compared to those found in natural teeth [2,3], and visual shade matching is affected by many factors such as variable viewer interpretation and environmental influences [4]. Conversely, color-measuring devices are efficacious to quantify the natural tooth color and enable communication between technicians and dentists to be more uniform and accurate.

In recent years various clinical color-measuring devices such as the spectrophotometer and the colorimeter have become available [5]. These devices have made it possible to analyze tooth color precisely and easily, making color-measuring devices indispensable to esthetic dental treatment [6]. In addition, the increasing public demand for esthetic dentistry has improved dental materials and techniques, and there has also been a demand for miniaturized color-measuring devices that can be more accurately and conveniently handled.

The purpose of this study was to evaluate the clinical performance of a dental color analysis system, the Crystaleye Spectrophotometer® (Olympus, Tokyo, Japan).

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Fig. 1. The Crystaleye Spectrophotometer®.

Fig. 2. Clinical setting for measuring tooth color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2. Materials and methods

The Crystaleye Spectrophotometer® uses light-emitting devices (LEDs) as an illumination source, with 45/0° geometry (Fig. 1). The color-measuring section consists of a spectrophotometer with a liquid crystal display (LCD) monitor, a cradle for calibration and data transmission to the computer, and a contact cap. Prior to color measurement, the Crystaleye Spectrophotometer® was calibrated using a reference plate installed at the edge of the cradle. As a result, the necessary standard color information for measuring could be obtained. After calibration, a contact cap was attached, and the color measurement was started. The spectrophotometer was moved to adjust the position of the tooth to be captured (Fig. 2). The captured images were automatically transmitted and processed via a USB cable to a personal computer with the Crystaleye Application Master® software for image analysis. Crystaleye Application Master® automatically identifies the color-measuring area of the cervical, body, and incisal areas of the target tooth, and color analysis data of the three areas are displayed. Furthermore, facial and arch images can be captured by changing the settings of the spectrophotometer. The laboratory report, which includes color information, is transmitted as electronic information. The accuracy of the fabricated crown using the information provided by the Crystaleye Spectrophotometer® can be evaluated within a special check box to simulate the oral cavity.

2.1. Reliability of color measurement from three color-measuring devices

Color measurements of the maxillary left central incisors were performed three times using the Crystaleye Spectrophotometer®, Color Analyzing Spectrophotometer-Iwate Medical University School of Dentistry Type 1 (CAS-ID1), and a multispectral camera system (MSC-2000; Olympus, Tokyo, Japan). For the purpose of comparing differences among the three color-measuring devices, the Scheffe's F-test was used for analysis.

2.2. Evaluating the accuracy of repeated color measurements

The color measurements of the maxillary left central incisors were performed 10 times by the same examiner in a lighted room and color difference (ΔE) between the first and tenth measurement was calculated and analyzed.

2.3. Effect of exterior lighting on color measurements

For analyzing the effects of exterior lighting on the accuracy of color measurement, the color of the maxillary left central incisors was measured three times in lighted and darkened rooms. The difference between the two conditions was compared using the t-test. A P value <0.05 was considered statistically significant.

2.4. Effect of the examiner on the color measurement

The color of the maxillary left central incisor was measured three times by five examiners, and for the purpose of comparing differences among the five examiners, the Scheffe's F-test was used in analysis.

2.5. Evaluating the reproducibility of tooth color using the Crystaleye Spectrophotometer®

A 28-year-old man in need of a single maxillary central incisor crown was recruited for this study. After endodontic treatment was performed, the maxillary left central incisor was prepared for the all-ceramic crown, and the fiber composite post (FibreKleer® Post system; Pentron Wallingsford, Connecticut, USA) was cemented with dual curing resin cement and the core was built-up with the recommended core resin. An impression was taken with a self-wetting hybrid polysiloxane impression material (Fusion II; GC, Tokyo, Japan), and the all-ceramic crown (Procera AllCeram System; Nobel Biocare, Gothenburg, Sweden) was fabricated for the single maxillary central incisor using the data from the Crystaleye Spectrophotometer®. The target tooth color was measured three times from three regions

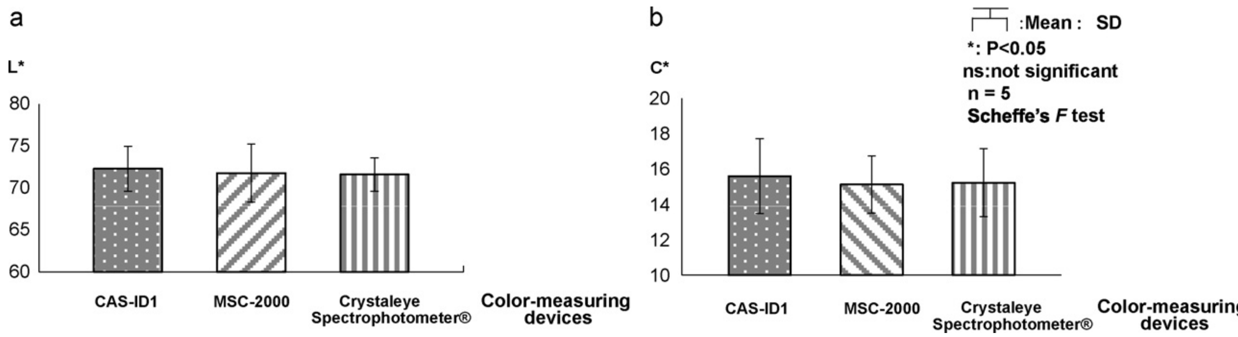

Fig. 3. Reliability of color measurement from the three color-measuring devices. (a) Mean L^* values for the three color-measuring devices. (b) Mean C^* values for the three color-measuring devices.

(cervical, body, and incisal regions per tooth) of contralateral central incisors using the Crystaleye Spectrophotometer®. The target tooth color data were analyzed, and a laboratory report was created. A laboratory report is based on the interpretation of the color data of the target tooth and closest shade to three regions using split images and numerical color data of the CIELAB color system. The all-ceramic crown was fabricated with use of the laboratory report and the color of the fabricated crown was measured and modified as necessary. The completed crown was positioned on the prepared tooth and three regions were measured. The color match was evaluated with ΔE between the target teeth and the completed crown.

2.6. Evaluating the effectiveness of tooth bleaching using the Crystaleye Spectrophotometer®

To analyze the efficacy of bleaching on tooth color changes, the teeth of a 35-year-old woman were bleached with the 10% carbamide peroxide bleaching system (NiteWhite, Discus Dental, Culver City, California, USA), and the color measurements were performed three times with the Crystaleye Spectrophotometer®. The color changes between prebleaching and postbleaching were analyzed using the ΔE, ΔL^*, Δa^*, and Δb^* values.

All color data were expressed in terms of L^*, a^*, and b^* in accordance with CIELAB color space. L^* represents lightness, a^* represents the chromaticity coordinate in a red–green direction, and b^* represents the chromaticity coordinate in a yellow–blue direction. C^* is called metric chroma and given by the equation $C^* = (a^{*2} + b^{*2})^{1/2}$.

ΔE refers to the color difference between two specimens and given by the equation

$$\Delta E = \{(L^*_{\text{target}} - L^*_{\text{standard}})^2 + (a^*_{\text{target}} - a^*_{\text{standard}})^2 + (b^*_{\text{target}} - b^*_{\text{standard}})^2\}^{1/2}.$$

ΔL^*, ΔC^*, Δa^*, and Δb^* values described below.

$$\Delta L^* = L^*_{\text{target}} - L^*_{\text{standard}}, \quad \Delta C^* = C^*_{\text{target}} - C^*_{\text{standard}}, \quad \Delta a^* = a^*_{\text{target}} - a^*_{\text{standard}}, \quad \Delta b^* = b^*_{\text{target}} - b^*_{\text{standard}}$$

All statistical analyses were performed with the aid of SPSS version 15.0 for Windows (SPSS Japan Inc., Tokyo, Japan).

This study was performed at Iwate Medical University with the approval of the institutional review board.

3. Results

3.1. Reliability of color measurement from three color-measuring devices

The mean L^* value of the maxillary central incisors obtained with the Crystaleye Spectrophotometer® was 71.6 ± 2.0, and the mean C^* value was 15.2 ± 1.9. The mean L^* value of the maxillary central incisors obtained with CAS-ID1 was 72.3 ± 2.7, and the mean C^* value was 15.6 ± 2.0. The mean L^* value of the maxillary central incisors obtained with the MSC-2000 was 71.8 ± 3.5, and the mean C^* value was 15.1 ± 1.6. The statistical analysis (Scheffe's F-test) indicated no significant difference for the L^* and C^* values among the three color-measuring devices (Fig. 3).

3.2. Evaluating the accuracy of repeated color measurements

The mean L^* value of the 10 repeated measurements for the maxillary central incisor was 72.1 ± 0.5, and the mean C^* value was 14.8 ± 0.3 (Fig. 4). The ΔE between the first through the tenth measurements ranged from 0.1 to 0.9, and the mean ΔE was 0.6 ± 0.3.

3.3. Effect of exterior lighting on color measurements

The mean L^* value of the maxillary central incisors in the lighted room was 72.1 ± 0.2, and the mean C^* value was 14.8 ± 0.3. In the dark room, the mean L^* value was 71.9 ± 0.7, and the mean C^* value was 15.0 ± 0.5 (Fig. 5). The ΔE between the two conditions was 0.9. The statistical analysis (t-test) indicated no significant difference for the L^* and C^* values between the two conditions.

3.4. Effect of the examiner on the color measurement

The mean L^* value of the five examiners was 72.6 ± 0.4, and the mean C^* value was 15.8 ± 0.3. The statistical

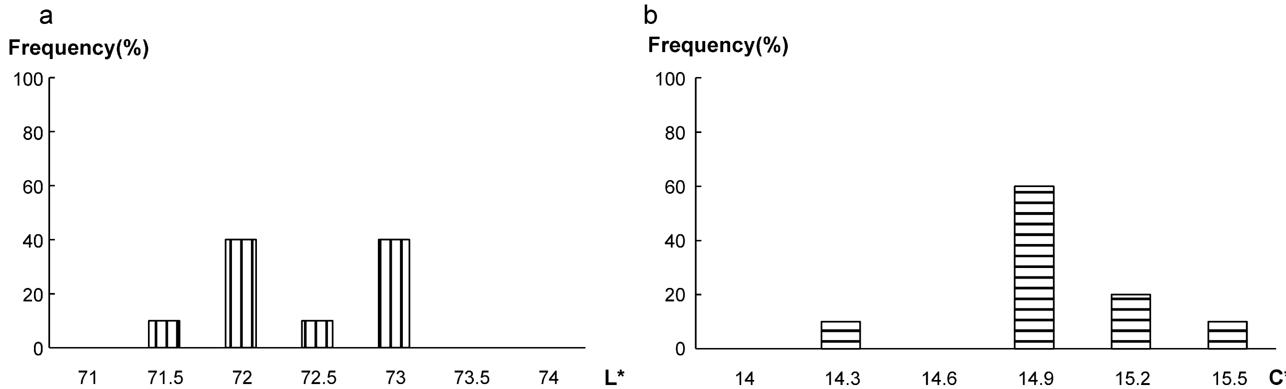

Fig. 4. Evaluating the accuracy of repeated color measurements. (a) Frequency distribution of L^* value for 10 repeated measurements. (b) Frequency distribution of C^* value for 10 repeated measurements.

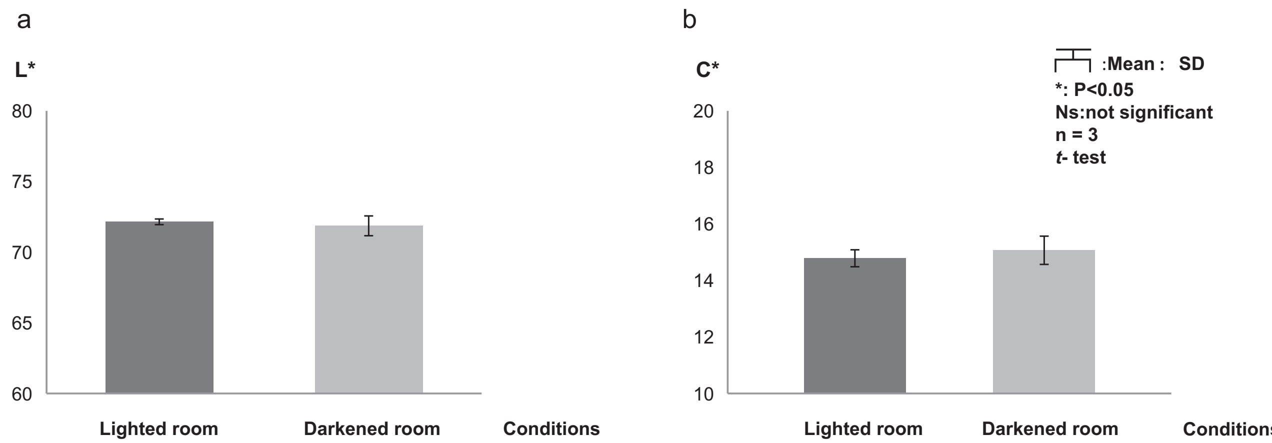

Fig. 5. Effect of exterior lighting on color measurement. (a) Mean L^* value for the two conditions. (b) Mean C^* value for the two conditions.

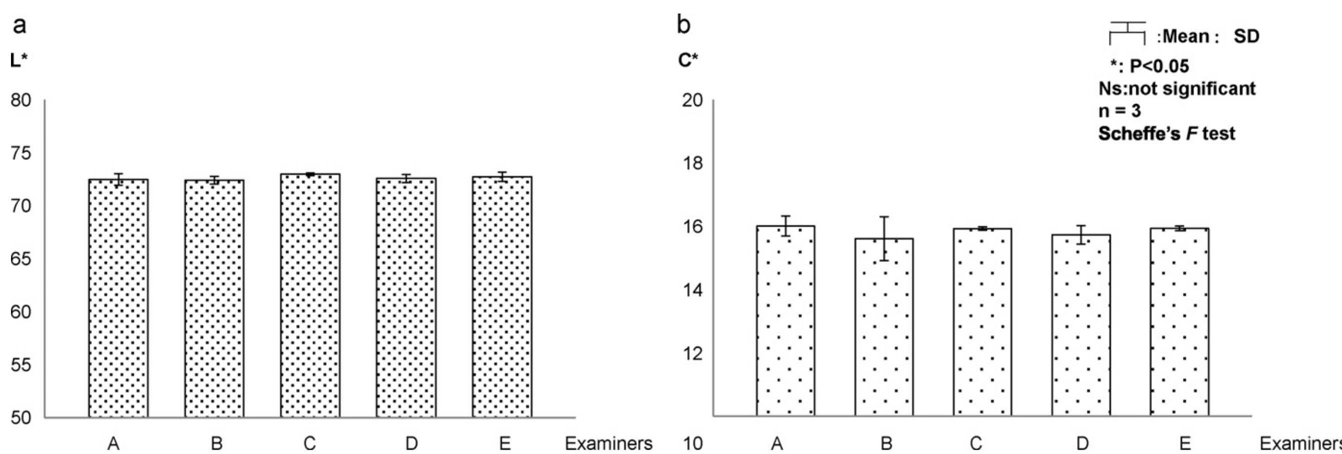

Fig. 6. Effect of the examiner on color measurement. (a) Mean L^* values for five different operators. (b) Mean C^* values for five different operators.

analysis (Scheffe's F-test) indicated no significant difference for the L^* and C^* values among the five examiners (Fig. 6).

3.5. Evaluation of tooth color reproducibility using the Crystaleye Spectrophotometer®

The mean ΔE between the target teeth and the fabricated crown was 1.2 ± 0.4. The mean ΔE was 1.0 ± 0.1 in the cervical area, 1.7 ± 0.1 in the body area, and 0.8 ± 0.1 in the incisal area (Fig. 7).

3.6. Evaluation of the effectiveness of tooth bleaching using the Crystaleye Spectrophotometer®

The mean ΔE between prebleaching and postbleaching was 3.7 ± 1.0. The mean ΔL^*, Δa^*, and Δb^* values were 0.4 ± 2.6, -0.5 ± 0.5, and -2.8 ± 1.4 (Fig. 8).

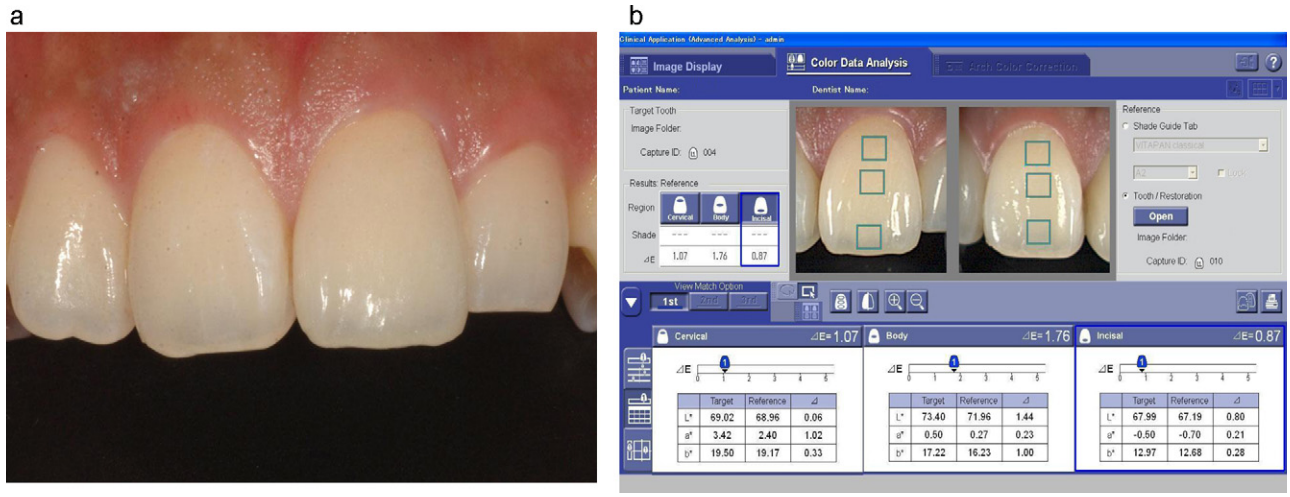

Fig. 7. Evaluation of tooth color reproducibility using the Crystaleye Spectrophotometer®. (a) Intraoral view of the all-ceramic crown attached to the maxillary central incisor. (b) Image display and color data analyzed by the Crystaleye Spectrophotometer®.

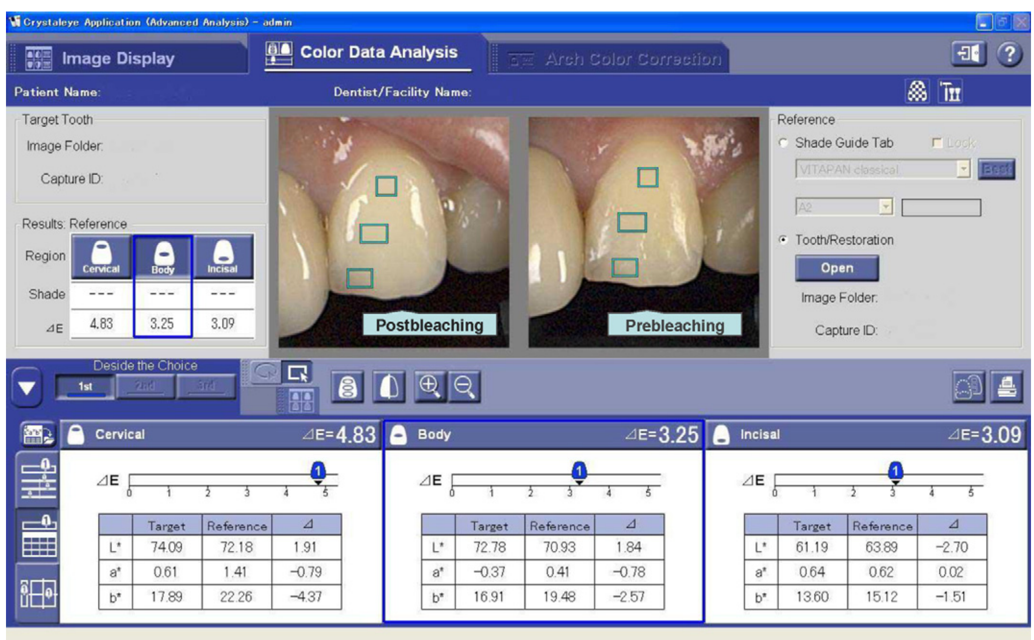

Fig. 8. Image display and color data analyzed by the Crystaleye Spectrophotometer®.

4. Discussion

Color measurement of natural teeth is important for improving color reproduction. Evaluating the natural teeth color is performed either by visual shade matching or instrumental color analysis [7]. Visual shade matching is affected by many factors, such as human physiologic variables and surrounding illumination [8]. Many types of instrumental color analysis devices have been developed and are now available for dental use [9], but the spectrophotometer is the most suitable device for providing both systematic and precise measurements of tooth color [10]. Furthermore, spectrophotometer functions need to be miniaturized and the handling of such options must be simplified. The Crystaleye Spectrophotometer® is a noncontact-type spectrophotometer that uses LEDs as an illumination light source and it produces the geometrical conditions needed to measure natural teeth. Furthermore, the LCD monitor in the spectrophotometer aids in image location and focus. Therefore, the Crystaleye Spectrophotometer® is a system in which no errors should occur during the color-measuring procedure, and therefore it is useful in clinical conditions.

We evaluated the precision of the measurements made with the Crystaleye Spectrophotometer® by comparing its performance to those of a CAS-ID1 and MSC-2000. In this study, the CAS-ID1 was used as the standard device. The geometry of the CAS-ID1 was the most appropriate for measuring small areas and made precise measurements for clinical use [11]. The CAS-

ID1 and Crystaleye Spectrophotometer® showed similar values, which demonstrated that the Crystaleye Spectrophotometer® is sufficiently accurate for measuring natural tooth color. The MSC-2000 uses a multispectral camera system by which the actual measurement is performed for each area chosen from multispectral images or the digital images of an entire object that features spectral data for each pixel. The light source for illumination of the MSC-2000 was a 100-W tungsten halogen lamp, and it was connected by a cable to a probe with a hemispheric light trap, thus comprising the color-measuring unit [12,13]. In short, the similar color values between the Crystaleye Spectrophotometer® and the MSC-2000 showed that although the Crystaleye Spectrophotometer® is a handheld spectrophotometer without a cable, it is not affected by changes in light source or color-measuring head, and retains the function of a multispectral camera system.

Thus three color-measuring devices are spectrophotometers designed to produce accurate measurements because of their ability to measure the amount of light reflected from target teeth, and three spectrometric measurements led to the similar values.

In clinical dentistry, it is difficult to evaluate tooth color under ideal conditions, and it is useful to use a color-measuring device that produces constant values under any given condition. Furthermore, the ease of use and degree of sensitivity affect the measuring time and movement producing changes in the measuring-color values. In particular, it is important that constant color values can be determined repeatedly in a clinical situation, and it is also desirable that individuals who take the measurement produce stable values under different conditions. Therefore, in this study, we examined the stability of the determined color value, the effect of the surrounding area, and evaluated differences resulting from measurements taken by different individuals. Results from ΔE between lighted and darkened conditions and the statistical analysis of the $L^*$and C^* values among the five examiners indicated that the geometry of the Crystaleye Spectrophotometer® was most appropriate for measuring natural teeth, and the measuring time improved its clinical utility.

The assessment of clinical utility for the fabrication procedure was performed by reproducing the color gradation of natural teeth to fabricate the all-ceramic crown using the software function of the Crystaleye Spectrophotometer®. In clinical practice, the transfer of data regarding natural tooth color between the dentist and dental technicians at a different location is challenging. The structure of natural teeth is complex and includes characteristics such as translucency and gloss so that illustrations, which do not consider such factors, lack full information [14]. This discrepancy makes it difficult to supply information to dental laboratory technicians through illustrations. In recent years, the use of commercial digital cameras has increased [15]. However, images taken by commercial digital cameras are influenced by the surrounding conditions and the set-up of the digital camera, and hence, it is difficult to evaluate natural teeth by numerical color data. The Crystaleye Application Master® is color analysis software that provides a combination of numerical color data and photographic images.

In this study, the all-ceramic crown was fabricated using this information, and the fabricated crown was measured within a special check box to simulate the oral cavity so that it could be modified as necessary. The results of the mean ΔE between the target teeth and the fabricated crown indicated that the software function is useful for quality control during the fabrication procedure. Successful fabrication of all-ceramic crown systems requires a complex process consisting of multiple steps [16]. The Crystaleye Spectrophotometer® supports these steps and improves the accuracy of the fabricated crown. Moreover, analysis of the color gradation data from the incisal to the cervical areas is useful for selecting the appropriate all-ceramic crown system and to judge whether it is an individually layered crown or a crown milled from machinable ceramics using the CAD/CAM system.

Vital tooth bleaching is an increasingly requested esthetic treatment. The Crystaleye Spectrophotometer® can evaluate the efficacy of vital tooth bleaching on tooth color changes using numerical color data. Moreover, the numerical color data allow us to plan and control the bleaching treatment. Analysis of color change data would be helpful so that patients can evaluate their treatment outcomes.

The results of this study show that the Crystaleye Spectrophotometer® is an easy-to-use color analysis system that produces accurate color measurements under clinical conditions. This system improves the color replication process objectively.

Although the human eye is the final arbitrator, it is necessary to establish exact an relationship between visual shade-matching and instrumental color analysis The Crystaleye Spectrophotometer® supports these relationships and enhances the ability to esthetically match restorations.

5. Conclusion

Within the limitations of this study, the following conclusions were made:

1. The CAS-ID1 and the MSC-2000 were tested and compared with the Crystaleye Spectrophotometer®, and there were no significant differences for the L^* and C^* values among the three color-measuring devices.
2. Repeated color measurements with the Crystaleye Spectrophotometer® were performed 10 times by the examiner and ΔE between the first and tenth measurement was calculated. The ΔE ranged from 0.1 to 0.9, and the mean ΔE was 0.6 ± 0.3.
3. The color values of the maxillary left central incisors were measured with the Crystaleye Spectrophotometer® in a lighted room and a darkened room. The statistical analysis indicated no significant difference for the L^* and C^* values between the two conditions.
4. Five different examiners measured the maxillary left central incisor with the Crystaleye Spectrophotometer®, and the statistical analysis indicated no significant difference for the L^* and C^* values among the five examiners.

5. A single maxillary crown was fabricated using the Crystaleye Spectrophotometer®. The mean ΔE value of the measurement areas between the target teeth and the fabricated crown was 1.2 ± 0.4.
6. The mean ΔE value of the tooth color between prebleaching and postbleaching was 3.7 ± 1.0. The mean ΔL^*, Δa^*, and Δb^* values were 0.4 ± 2.6, -0.5 ± 0.5, and -2.8 ± 1.4.

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