Odontology
https://doi.org/10.1007/s10266-022-00694-9

ORIGINAL ARTICLE

# Evaluation of accuracy and characteristics of tooth-color matching by intraoral scanners based on Munsell color system: an in vivo study

**Mingming Huang[1] · Hongqiang Ye[1,2] · Hu Chen[1] · Yongsheng Zhou[2] · Yunsong Liu[2] · Yong Wang[1] · Yuchun Sun[1]**

Received: 16 October 2021 / Accepted: 10 February 2022


## Abstract

To compare the accuracy of visual and instrumental methods for tooth-color matching based on three attributes in the Munsell color system and to investigate the characteristics of intraoral scanners for tooth-color matching. Shades of the cervical, middle, and incisal third region of 130 maxillary anterior teeth were matched visually by an experienced prosthodontist (EP) using Vita classical A1-D4 (VC) and Vita System 3D-Master (V3D) shade guides, and digitally by a spectrophotometer (Vita Easyshade V, VE) and two intraoral scanners (3Shape TRIOS 3, T3; TRIOS 4, T4). VE was used as a reference. The reproducibility of the three test groups was examined by repeating the measurements in triplicate. The overall trueness of the three test groups (from high to low) was T3 > EP > T4 for VC values ($p < 0.01$), and T3, EP > T4 ($p < 0.01$) for V3D. The trueness of T3 in incisal regions was lower than cervical and middle regions. When hue or lightness was correct, the mismatched chroma in test groups was smaller than VE ($p < 0.01$). The repeatability of EP was the poorest ($p < 0.01$). The color-matching trueness of T3 was higher than EP and T4. The reproducibility of intraoral scanners was better than visual methodology.

**Keywords** Shade matching · Shade guide · Spectrophotometer · Intraoral scanner · Visual

Mingming Huang and Hongqiang Ye contributed equally to this work.

✉ Yong Wang
kqcadc@bjmu.edu.cn

✉ Yuchun Sun
kqsyc@bjmu.edu.cn

1 Center of Digital Dentistry, Faculty of Prosthodontics, Peking University School and Hospital of Stomatology, National Center of Stomatology, National Clinical Research Center for Oral Disease, National Engineering Research Center of Oral Biomaterials and Digital Medical Devices, Beijing Key Laboratory of Digital Stomatology, Research Center of Engineering and Technology for Computerized Dentistry Ministry of Health, NMPA Key Laboratory for Dental Materials, No. 22, Zhongguancun South Avenue, Haidian District, Beijing 100081, China

2 Department of Prosthodontics, Peking University School and Hospital of Stomatology, National Center of Stomatology, National Clinical Research Center for Oral Disease, National Engineering Research Center of Oral Biomaterials and Digital Medical Devices, Beijing Key Laboratory of Digital Stomatology, Research Center of Engineering and Technology for Computerized Dentistry Ministry of Health, NMPA Key Laboratory for Dental Materials, Beijing 100081, China

## Introduction

Tooth color, arrangements, positions, proportions, shapes, and morphologies, are the foundations of esthetic dentistry [1]. With the development and popularization of digital technology, it is very convenient to ensure that the position and contour of esthetic restorations perfectly meet all esthetic rules and guidelines with the assistance of computer-aided methods [2]. However, unmatched color will still lead to unsatisfaction. Therefore, it is important that we identify how digital technology can precisely identify and simulate the true color of teeth, predict the color of the esthetic outcome, and ultimately ensure that the final color mimics the natural tooth as closely as possible. The accurate selection of tooth shade is essential if we are to achieve an acceptable esthetic outcome [3].

Visual and instrumental methods are the primary tools used to select tooth shade. In clinical practice, the visual method selects the best color match for a target tooth by comparing to a commercial shade guide. Modern shade guides, typically represented by Vita classical A1-D4 (VITA Zahnfabrik, Bad Säckingen, Germany) and Vita System 3D-Master shade guides [4, 5], are usually arranged using

Published online: 25 February 2022

the Munsell color system and grouped by hue, lightness, and chroma [6]. Visual tooth-color matching is quick and economical; however, this method is thought to be subjective and subject to many error sources, such as light conditions, shade guides, the age and psychological state of the observer, eye fatigue, color vision deficiency, and clinical experience [7–10]. In addition, the tooth color and the determination of tooth color is complex; although the human eye can discern very small differences in tooth color in an efficient manner [11, 12], there is no standardized protocol for verbally communicating visually assessed color characteristics between doctors, technicians, and patients. Therefore, it is still difficult to accurately express such differences in relation to restorative desire and patient requests [13, 14]. By applying light correction, shade guides use training, color education, and the accumulation of experience, to improve the ability of an individual to discriminate between colors, thus improving the quality of visual shade matching [3, 15–17].

A variety of instruments are now available to assist in color determination, including spectrophotometers, colorimeters, spectroradiometers, and digital cameras and imaging systems [18]. These systems can eliminate subjective variables during observation, discover, and measure subtle differences between objects, and facilitate communication between dentists and technicians [10, 11, 19]. Spectrophotometers are currently thought to be one of the most accurate, useful, and flexible instruments for the determination of color [10, 20, 21]. Spectrophotometers can measure the amount of light energy reflected from an object at 1–25 nm intervals along the visible spectrum and can convert the measured spectral reflectance to color coordinates and various dental shade guide values [11, 18]. However, the color-measuring devices used in dentistry may be associated with an edge loss effect that could lead to incorrect and inconsistent results [18, 22, 23].

Over recent years, a range of powder-free intraoral scanners (IOSs) has been developed that can determine tooth color, including the 3Shape TRIOS (3Shape A/S, Copenhagen, Denmark), the CEREC Omnicam (Sirona Dental Systems, Bensheim, Germany), and the CEREC Primescan [24]. The 3Shape TRIOS employs the photographic system and a form of technology referred to as ultrafast optical sectioning. This technique combines confocal microscopy with the projection of structured light to acquire in-focus images from selected depths and reconstructs data by transforming contrast information *versus* the position of the focus plane into three-dimensional (3D) surface information pixel by pixel [25–28]. These powder-free systems enable the acquisition of 3D information from tooth surfaces and creates a photorealistic copy of the tooth color [29], thus simplifying the workflow of color matching and bring convenience to dentists and technicians. Previous studies have reported wide variation in the tooth-color matching capability of IOSs [9, 20, 24, 29–34]. Furthermore, there has been little research focused on the characteristics of mismeasurements with IOS. Therefore, there is a clear need to analyze the tooth-color matching function of the IOS.

Therefore, the aim of this study was to use in vivo data to compare the accuracy (trueness and repeatability) of visual and IOS methodology for tooth-color matching and preliminarily investigate the characteristics of tooth-color matching with IOS based on the three attributes of the Munsell color system. Our null hypothesis was that no significant difference would be identified in the trueness and repeatability of tooth-color matching when comparing visual and IOS methods.

## Materials and methods

Ethical approval was granted by Peking University School and Hospital of Stomatology (PKUSSIRB-202058151) and all participants provided informed consent.

The study included 23 Chinese volunteers (7 males and 16 females) aged $26.8 \pm 2.6$ years with at least one vital and intact maxillary anterior tooth (FDI teeth: 13–23). Any restored, bleached, congenital or acquired color changes were excluded (e.g., demineralization, fluorosis, hypoplasia of the enamel, or severe pigmentation) [20]. Therefore, 5 decayed teeth and 3 restorations were excluded from the 138 anterior maxillary teeth. The color of the cervical, middle, and incisal third region of each qualified tooth was measured. The sample size needed to achieve a power of 80% with a significance level of 0.05 (adjusted to 0.017 according to pairwise comparisons) was determined to be 124 teeth, as determined by a power calculation in PASS software (PASS 15, NCSS LCC, Utah, USA). Overall, 130 teeth were included in this study and the shades of 390 sites were recorded.

All measurements in the study were conducted in the same enclosed room with no windows or natural light. The ceiling lighting in the room was standardized daylight lamps with a color temperature of 6500 K (TL-D Graphica 965 Philips, Amsterdam, Netherlands). The ambient light illuminance of the room was 1010 lx which was measured using a light meter (DLY-1802 Light Meter, Delixi, Zhejiang, China) [9, 30, 35]. Prior to shade matching, each subject was told to remove makeup and brush teeth for 2 minutes with a soft toothbrush and a regular toothpaste. This procedure eliminated soft deposits, and ensured that the teeth were clean and slightly moistened. Next, we covered the participant's clothes with a gray cape. During shade matching, the subject was instructed to sit on the same chair with their body in a fixed position, their mouth slightly open, and their tongue in a relaxed position. This was because pressing the tongue against the front of the maxillary may result in mismeasurements due to incisal tooth translucency [36].

## Visual color determination

One prosthodontist with 10 years of experience in superior color-matching competency participated in visual shade matching; this prosthodontist had passed the Ishihara color blindness test (ISO TR 28,642:2016) [37] without any incorrect answers.

When visual shade matching, the observer's eyes were held at the level of the subject's mouth. The shade guide was held with a bent arm, directly in front of the subject's tooth. The incisal edge of the shade guide tab was positioned against the incisal edge of the target tooth (Fig. 1). Furthermore, according to the manufacturer's instructions and previous studies [7, 34], the observer compared the shade tabs with each tooth in its cervical, middle, and incisal third in a rapid manner. The observer needed to accept the first decision since the eyes may begin to tire after 5–7 s. Therefore, an A4 sheet of 18% gray card was used to rest the observer's eyes between shade assessments. During this period, the subject was told to close their mouth and moisten their teeth with saliva to prevent the color becoming lighter due to dehydration [38, 39].


**Fig. 1** Intraoral image of visual tooth-color determination using the shade tab of the Vita System 3D-Master shade guide

Due to their respective popularity, the Vita classical A1-D4 (VC) and Vita System 3D-Master (V3D) shade guides were used as the basis for this study [11, 40]. The VC features 16 tabs that are ordered into four hue groups: A (reddish-brownish), B (reddish-yellowish), C (grayish), and D (reddish-grayish). Depending on the hue, these can be further grouped by increasing chroma; these were designated in numerical order; the more chromatic tabs were marked with higher numbers [5]. Shades were determined in the order of hue first, and then chroma. The V3D features 29 tabs and was regularly divided into six groups of tabs by lightness, from 0 (the lightest) to 5 (the darkest). There were three chroma levels, from 1 (the least chromatic) to 3 (the most chromatic) in each group of lightness (except the lightness 1 group that had two chroma levels 1 and 2) of hue M (neutral). Intermediate chroma levels (1.5 and 2.5) in groups 2, 3, and 4 were associated with hue L (yellow) and R (red). Shades were determined in the following order: lightness, then chroma, and finally, hue [4, 5].

For each subject, the observer visually matched all target sites with one random shade guide, and then with another. Visual color determination was repeated three times to compare consistency. The color matching outcomes of this group were recorded as the EP group.

## Instrumental color determination

The instruments used in this study included a spectrophotometer (Vita Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany) and two IOS systems (Model S1P-1 and S3P-2, TRIOS 3 and 4, 3Shape A/S, Copenhagen, Denmark). All instrumental matching procedures were carried by the same trained operator.

### Vita easyshade V (VE)

According to the manufacturer's instructions, the measuring tip was fitted with a disposable protective cap before being applied to each subject. Then, the VE was placed in its charging station so that the tip could lie flush on the calibration block to carry out white balance. When calibration was complete, the VE was set up to averaged shade determination mode and the measuring tip was positioned in close contact with the tooth surface to measure each site in turn (Fig. 2). The measurement results were displayed by VC and V3D values and recorded as the VE group.

### 3Shape TRIOS 3 and 4 (T3 and T4)

According to the manufacturer's instructions, the T3 needed to be calibrated before use. Maxillary anterior teeth and

**Fig. 2** Intraoral image of instrumental tooth-color determination using the Vita Easyshade V spectrophotometer

neighboring teeth were scanned from the vestibular, incisal, and palatal aspects [9, 20, 34]. The quality of the color data acquired by T3 was monitored by the built-in shade function. Any target area marked blue was additionally scanned from different angles to obtain complete color information [29, 41]. Once scanning was complete, the color measurement mode was applied to determine the shades of each site on the target teeth from the captured digital impression (Fig. 3). The T4 was used for scanning and measuring tooth color using the same procedure. Instrumental color determination by the T3 and T4 was repeated three times to compare consistency.

The order followed for the IOS groups was randomized. Both the T3 and T4 were configured to provide results as VC and V3D values. All digital models were saved and the matching outcomes of the two IOSs were recorded as the T3 group and T4 group, respectively.

## Data analysis

In the present study, the VE was used as the reference device to evaluate the trueness of the three test groups (EP, T3, and T4). At the beginning, the final shade was summarized following the principle of majority. At each site, if all of the three repeated measurements of one specific test group selected the same shade tab twice or more, then this shade was selected as the final shade for the group chosen for this site. If the results of three repeated measurements differed, then the first determination was used as the final shade. Since three attributes in the Munsell color system (hue, chroma, and lightness) served as the foundation for analysis to compare trueness, the final shades for each test group, and the measurement results of the control group (VE), were split according to the design principle of the two shade guides for further analysis. For example, shade number A1 in VC was split as hue A and chroma 1 while shade number 2M1 in V3D was split as lightness 2, hue M, and chroma 1.

Since shades were determined in the order of hue followed by chroma, the VC results of each test group were first compared with the control group by hue, and then in the correct results, the same results between each test group and control group were screened out according to chroma. The data processing method for analyzing the trueness of each test group when using V3D was the same as above and was carried out in the following order: lightness, then chroma, and finally hue.

With regards to the repeatability of each test group, all measurements were repeated in triplicate. The proportion of triplicate results at the same site in each test group was calculated for further evaluation.

## Statistical analysis

Trueness was calculated as a percentage of the correct color match. Repeatability was assessed by considering the proportions of repeated measurements from the same site. Categorical variables are presented as frequencies ($n$) and

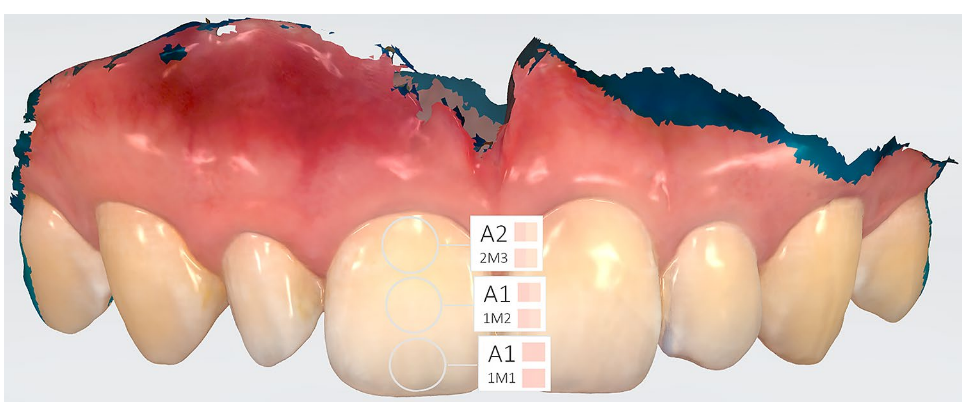


**Fig. 3** Screenshot of the digital scans completed by the 3Shape TRIOS 3 with tooth-color matching performed in the cervical, middle, and incisal third of the maxillary right central incisor with reference to the Vita classical A1-D4 and Vita System 3D-Master shade guides values

percentages (%). The trueness and repeatability of measurement were compared using Pearson's Chi-squared test followed by multiple comparisons using Bonferroni tests. When each test group had the correct hue but incorrect chroma in VC, when each test group had the wrong lightness, and when each test group had the correct lightness but the wrong chroma in V3D, then the incorrect measurements, and the corresponding measurements of VE, were checked for significant differences using Wilcoxon's signed-rank test. The statistical significance level was set to 0.05 and the significance level was adjusted to 0.017 (3 comparisons among 3 groups) or 0.008 (6 comparisons among 4 groups) after Bonferroni corrections according to the number of pairwise comparisons. Statistical analysis was performed using SPSS software (SPSS Statistics 25, IBM, New York, USA).

## Results

In total, 130 maxillary anterior teeth were included in this study with 130 cervical third sites, 130 middle third sites, and 130 incisal third sites. The color matching results according to two shade guides were, respectively, counted according to the VE reference device. In VC, there were 231 sites in hue A, 157 sites in hue B, and 2 sites in hue C. Due to the small sample size, the 2 sites of hue C were not included in subsequent analysis. In V3D, there were 16 sites in lightness 1, 250 sites in lightness 2, 94 sites in lightness 3, and 30 sites in lightness 4.

### Measurement of trueness

When VC was used to record the results, there were two dimensions for comparison: hue; and hue and chroma.

In both dimensions, the trueness rate of the three test groups in all measured sites ranked in order from high to low was T3 > EP > T4 ($p < 0.001$), the trueness rates of T3 and T4 for the cervical and middle regions were higher than in the incisal regions ($p < 0.001$) (Table 1), the trueness rates of T4 and EP for hue A were higher than that for hue B ($p < 0.001$). For T3, the trueness rates for hue A and hue B were not significantly different when compared between the two dimensions (Table 2). When T3, T4, and EP had the correct hue but wrong chroma, the incorrect measurements' chroma was lower than the corresponding measurements' chroma according to VE ($p < 0.001$) (Table 3).

When V3D was used to record data, there were three dimensions for comparison: lightness; lightness and chroma; and lightness, chroma and hue.

In the third dimension, the trueness rate for the three test groups in all measured sites ranked in order from high to low was T3, EP > T4 ($p < 0.001$), the trueness rates of

**Table 1** Values and statistical differences for the rate of trueness (%) for all sites, cervical sites, middle sites, and incisal sites, in specific dimensions and a comparison of VC and V3D shade guides for all test groups

| Shade guide | Dimension for comparison | Method | Rate of trueness of sites (n) | | | |
|---|---|---|---|---|---|---|
| | | | All (n = 390) | Cervical (n = 130) | Middle (n = 130) | Incisal (n = 130) |
| VC | Hue | T3 | 63% A | 70% Aa | 71% Aa | 48% Ab |
| | | T4 | 40% B | 55% ABa | 50% Ba | 15% Bb |
| | | EP | 53% C | 52% Ba | 53% Ba | 55% Aa |
| | Hue & Chroma | T3 | 43% A | 52% Aa | 52% Aa | 25% Ab |
| | | T4 | 6% B | 8% Ba | 8% Ba | 2% Bb |
| | | EP | 30% C | 25% Ca | 35% Cb | 29% Aab |
| | Lightness | T3 | 47% A | 45% Aa | 43% Aa | 52% Aa |
| | | T4 | 34% B | 30% Ba | 39% Aa | 32% Ba |
| | | EP | 41% AB | 35% ABa | 42% Aa | 47% Aa |
| V3D | Lightness & Chroma | T3 | 28% A | 32% Aa | 32% Aa | 20% Aa |
| | | T4 | 3% B | 3% Ba | 3% Ba | 2% Ba |
| | | EP | 22% A | 20% Aa | 22% Aa | 22% Aa |
| | Lightness & Chroma & Hue | T3 | 27% A | 32% Aa | 32% Aa | 18% Ab |
| | | T4 | 3% B | 3% Ba | 3% Ba | 2% Ba |
| | | EP | 22% A | 20% Aa | 22% Aa | 22% Aa |

Different capital letters indicate statistical differences among the values of trueness for the three different methods (column) in each kind of sites (all, cervical, middle, incisal) in the same dimension using the same shade guide ($p < 0.017$)

Different lowercase letters indicate statistical differences among the values of trueness for the three different kinds of sites (line) in each method (T3, T4, EP) in the same dimension using the same shade guide ($p < 0.017$)

**Table 2** Values and statistical differences for the rate of trueness (%) for the two groups of hue in all test groups and in the two dimensions for comparison by the VC shade guide

| Dimension for comparison | Method | Rate of trueness of the group of Hue ($n$) | |
|---|---|---|---|
| | | A ($n=231$) | B ($n=157$) |
| Hue | T3 | 67% Aa | 58% Aa |
| | T4 | 59% Aa | 11% Bb |
| | EP | 89% Ba | 1% Cb |
| Hue & Chroma | T3 | 45% Aa | 41% Aa |
| | T4 | 10% Ba | 0% Bb |
| | EP | 49% Aa | 1% Bb |

Different capital letters indicate statistical differences among the values of trueness for the three different methods (column) in each group of hue (A, B) in the same dimension using VC ($p<0.017$)

Different lowercase letters indicate statistical differences between the values of trueness for group of hue A and group of hue B (line) in each method (T3, T4, EP) in the same dimension using VC ($p<0.05$)

**Table 3** $p$ values for the mismatched results of each test group when compared with VE

| Mismatched results | Method | $p$ value* |
|---|---|---|
| Correct hue but wrong chroma (VC) | T3 | <0.001 |
| | T4 | <0.001 |
| | EP | <0.001 |
| Wrong lightness (V3D) | T3 | <0.001 |
| | T4 | <0.001 |
| | EP | 0.116 |
| Correct lightness but wrong chroma (V3D) | T3 | <0.001 |
| | T4 | <0.001 |
| | EP | <0.001 |

*$p<0.05$ indicates statistical differences between the mismatched results of each method (T3, T4, EP) and VE

T3 in the cervical and middle regions were higher than in the incisal regions ($p=0.012$). In other conditions, there was no significant difference in the trueness of the three sites for each test group (Table 1). Furthermore, in each dimension within each test group, the trueness rate of the lightness 1 group was the highest ($p<0.001$), followed by lightness 2; lightness 4 tended to be the lowest (Table 4). When T3 and T4 had the wrong lightness, the incorrect measurements' lightness was lower than the corresponding measurements' lightness according to VE ($p<0.001$). When T3, T4, and EP had the correct lightness but wrong chroma, the incorrect measurements' chroma was lower than the corresponding measurements' chroma according to VE ($p<0.001$) (Table 3).

The overall color-matching trueness of T3, T4, and EP was significantly higher when the results were recorded as VC values than when recorded as V3D values ($p<0.05$) (Table 5).

### Measurement of repeatability

When using VC values, the percentage of repeatability was poorest for EP (47%; $p<0.001$). When using V3D values, the repeatability rate of the three method groups ranked in order from high to low was T3 (76%) > T4 (64%) > EP (43%) ($p<0.001$). The repeatability for T4 was significantly higher when using VC than V3D ($P=0.014$). There was no significant difference in the repeatability of T3 and EP when compared between the two shade guides ($p>0.05$) (Table 6).

## Discussion

By taking VE as the reference device, the results of this study indicated that the trueness of using T3 for color determination was better than that of the visual method. We also determined that the visual method was better than using T4 and that the repeatability of EP was the poorest. Therefore, the null hypothesis of this study was rejected because significant differences were found in both trueness and repeatability between T3, T4 and EP.

Based on previous research, human color perception, which is the result of a complex interaction between psychological and physical processes, is highly influenced by a variety of factors and thought to be subjective [8–10], while the color matching results of spectrophotometers are considered to be accurate and objective [10, 11, 20, 21, 30]. Although spectrophotometers have been reported to have an edge loss effect that can lead to incorrect and inconsistent values [18, 22, 23], the mode we selected in this study was averaged shade determination; this could reduce the error caused by this factor under the conditions used in our study, at least to some extent [20].

The visual shade determination in this study was conducted by an experienced prosthodontist with superior color-matching competency who had passed the Ishihara color blindness test and without incorrect answers. Consequently, our findings may not be representative for all prosthodontists. However, this did not affect the results found in this study with regards to identifying the advantages and disadvantages of the visual method. To be specific, the trueness of T3 in the incisal areas was significantly lower than that in the cervical and middle areas, and was also slightly lower than that of EP. These data implied that the color collection and recognition of T3 did not perform well in areas with high transparency while there were no such disadvantages for human eyes to determine the shades of different types of regions. Furthermore, the trueness rate of T3 for hue A was slightly lower than that of EP. This may have been

**Table 4** Values and statistical differences for the rate of trueness (%) for the four groups of lightness in all test groups, in the three dimensions for comparison by the V3D shade guide

| Dimension for comparison | Method | Rate of Trueness in the Group of Lightness ($n$) | | | |
|---|---|---|---|---|---|
| | | 1<br>($n$ = 16) | 2<br>($n$ = 250) | 3<br>($n$ = 94) | 4<br>($n$ = 30) |
| Lightness | T3 | 88% Aa | 48% Ab | 48% Ab | 10% Ac |
| | T4 | 81% Aa | 37% Bb | 23% Bb | 13% Ab |
| | EP | 88% Aa | 46% ABb | 29% Bc | 20% Ac |
| Lightness & Chroma | T3 | 75% Aa | 28% Ab | 29% Ab | 3% Ac |
| | T4 | 19% Ba | 3% Bb | 0% Bb | 0% Aab |
| | EP | 69% Aa | 25% Ab | 10% Cc | 7% Abc |
| Lightness & Chroma & Hue | T3 | 75% Aa | 26% Ab | 29% Ab | 3% Ac |
| | T4 | 19% Ba | 3% Bb | 0% Bb | 0% Aab |
| | EP | 69% Aa | 25% Ab | 10% Cc | 7% Abc |

Different capital letters indicate statistical differences among the values of trueness for the three different methods (column) in each group of lightness (1, 2, 3, 4) in the same dimension using V3D ($p < 0.017$)

Different lowercase letters indicate statistical differences among the values of trueness for four groups of lightness (line) in each method (T3, T4, EP) in the same dimension using V3D ($p < 0.008$)

**Table 5** Values for the rate of trueness (%) of all measured sites ($n$ = 390) for each test group using VC and V3D shade guides showing $p$ values for the overall trueness when using VC and V3D in each test group

| Method | Rate of overall trueness with the shade guide | | $p$ value* |
|---|---|---|---|
| | VC | V3D | |
| T3 | 43% | 27% | < 0.001 |
| T4 | 6% | 3% | 0.021 |
| EP | 30% | 22% | 0.009 |

*$p < 0.05$ indicates statistical differences within the values of overall trueness when using VC and V3D for the same method

**Table 6** Values and statistical differences for the rate of repeatability (%) for each method group in all measured sites ($n$ = 390) when using VC and V3D shade guides

| Method | Rate of overall repeatability with the shade guide | |
|---|---|---|
| | VC | V3D |
| T3 | 75% Aa | 76% Aa |
| T4 | 72% Aa | 64% Bb |
| EP | 47% Ba | 43% Ca |

Different capital letters indicate statistical differences among the values of overall repeatability for the three different methods (column) using the same shade guide ($p < 0.017$)

Different lowercase letters indicate statistical differences between the values of overall repeatability for using the two shade guides (line) by the same method ($p < 0.05$)

because visual measurement was better at identifying hue A, or because dentists, based on clinical experience, prefer to choose the shade number related to hue A when matching tooth color for young Chinese people, thus improving the trueness.

In this study, the repeatability of the two IOSs for VC and V3D was higher than that for the visual method. This result proved that human eyes tend to be unstable when measurements were repeated [30, 34, 42, 43]. Furthermore, the repeatability and trueness of the instrumental and visual method for VC were both higher than that for V3D. This could be caused by the different designs of the two shade guides. The larger number of shade tabs for V3D than for VC may lead to a higher possibility for inconsistency and mistakes during shade matching [32, 42, 44].

The obvious advantages of T3 shown in this study were its high trueness in hue B and lightness 1, 2, 3 when compared to T4 and EP. There was no significant difference detected between T3 and EP in terms of the trueness of hue A. These data imply that the measurement results of T3 can be considered as a reference, at least to some extent. However, the trueness of T4 was lower than that of T3. This may have been due to improvements in the hardware and software for T4 and its detailed design, thus influencing its color determination ability. The specific characteristics of T3 and T4 should now be explored further. This also highlighted the fact that the color matching results of the instruments should be carefully considered and applied. Dentists should select the appropriate method during clinical practice to convey the complex color information in the most comprehensive and accurate manner.

According to the analysis of mismatched color determination results, it was found that in terms of lightness, both T3 and T4 tended to select lighter color numbers. For chroma, the two IOSs and EP also tended to choose color numbers with a lower chroma. This represents the esthetic tendency of a preference for a whiter and brighter tooth color, as reported previously [8, 45]. This preference may influence the internal conversion setting of the instruments and the determination of dentists during color matching, thus resulting in the differences seen with VE outcomes. In addition, the rate of trueness for T3, T4, and EP in identifying lightness 4 was low; this may also have been caused by such preference factors.

On the one hand, the foundation of analysis in this study was the three attributes of the Munsell color system; these form the design principle underlying the two commonly used shade guides made by VITA. The Munsell color system, with three dimensions, is one of the most widely used color order system the system of choice for color matching in dentistry, including Hue, Chroma, and Lightness [46]. Hue is the quality by which we distinguish one color from another, such as the 5 principal hues, red, green, blue, yellow, and purple. And Chroma, is the intensity of a distinctive Hue. Lightness, or Value, is the quality by which we distinguish a light color from a dark color, and there are 10 main steps from pure black (0) to pure white (10) [47, 48]. The Munsell color system focuses on arranging colors with constant perceptual color difference for each perceptual attribute used, but hardly quantify the color for further analysis [49]. On the other hand, T3, T4 and human eyes cannot report color information via the color notation system (such as CIE L, a, b values) of the International Commission on Illumination, as with the VE [42, 50–52]. Therefore, all of the data used for statistical analysis in this study were categorical variables. Therefore, such limitations in the type of data would obscure the detail of tooth-color and fail to represent the true color precisely, at least to some extent; this may also have restricted the use of statistical methods. Similar problems have also been raised in some similar previous studies [20, 29, 30, 34], in which researchers used a conversion table with the help of a spectrophotometer to quantify the specific shade number to numerical variables to calculate color differences. However, since this type of conversion table was based on the spectrophotometer system, it may not be representative enough to reflect the accuracy and specific data conversion of other systems. In addition, during scanning, the detailed process of color image acquisition and conversion of the two 3Shape IOSs have not been revealed; this may result in the potential loss of color information that could not be measured [20, 30]. If the IOS can provide colorimetric data (such as CIE L, a, b values) and not just as VC or V3D values, then it would be able to evaluate the IOS's accuracy for color matching in a more accurate manner and provide detailed guidance for restoration fabrication.

With increasing age, the lightness of a tooth will decrease and the tooth-color will become more red and yellow [14, 53]. In this study, the mean age of the volunteers was 26.8 years. Moreover, the shade matching results of the VE system also showed that the samples in this study failed to cover all types of tooth color in terms of lightness, hue, and chroma; therefore, only partial colorimetric characteristics could be inferred for the T3 and T4 systems. The follow-up research should aim to increase the sample size, expand the age range and regional distribution of the volunteers, verify the results of this preliminary study, and explore the performance of each method under the conditions of lower lightness and higher chroma. Besides, in the present study, the maxillary anterior teeth were chosen to evaluate the accuracy and characteristics of tooth-color matching by IOS since the maxillary anterior teeth are of great significance in esthetic and restorative dentistry, and required to fulfill more esthetic guidelines [1, 54–56]. Further research could be carried out in the other regions, such as the premolar and molar area, to enlarge the possibility of IOS's shade-matching capability in the clinical application.

In clinical therapy, regardless of the method used for the measurement of tooth-color, the final assessments of whether the patient's expectations are met are always based on visual analysis [13]. This means that tooth-color determination prior to the fabrication of a prosthesis will represent the key foundation for the final esthetic outcome, especially in the anterior region. Dentists should display the color distribution of the tooth by various means and provide accurate and detailed laboratory prescriptions to convey all of the necessary information to dental technicians based on the individual and specific needs of the patient [3].

In this study, we performed an in vivo study to compare and evaluate the trueness and repeatability of T3, T4, and visual methodology and explored the characteristics of tooth-color matching by the two 3Shape IOSs. Our aim was to provide guidance for subsequent therapy and support for accurate personalized digital esthetic dentistry. Although IOSs with color measurement functionality are still unable to replace spectrophotometers, they can provide significant assistance for the determination of visual shade. With the development and improvement of digital technology, IOS can accurately obtain and reproduce the true color and characteristics of human teeth. The combination of efficient digital impression and color determination will bring significant advantages that can revolutionize the field of prosthodontics and even dentistry.

## Conclusion

Using two shade guides, we demonstrated that the trueness of T3 was higher than that of EP and T4 and that T3 performed well with regards to hue A, hue B, and lightness 1, 2, 3. However, the tooth-color determination function of the IOS systems was still inferior to the spectrophotometer. The repeatability of both IOS systems was better than the visual method meaning that the reliability of visual measurement was poor.

**Acknowledgements** This work was supported by the National Key R&D Program of China (2019YFB1706900); Capital Science and Technology Leading Talent Project (Z191100006119022); Program for New Clinical Techniques and Therapies of Peking University School and Hospital of Stomatology (PKUSSNCT-20B07); and PKU-Baidu Fund (2019BD021). The authors would like to express their gratitude to Ms. Yan Xiaoyan for her guidance on the statistical analysis of this research and to EditSprings for the expert linguistic services provided.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests in relation to the present study.

**Ethical approval** This study included 23 Chinese volunteers (7 males and 16 females) aged 26.8±2.6 years. All procedures performed in the present study involving human participants were in accordance with the Declaration of Helsinki. Ethical approval was granted by Peking University School and Hospital of Stomatology (PKUSSIRB-202058151).

**Informed consent** Informed consent was obtained from all individual participants included in the study.

## References

1. Blatz MB, Chiche G, Bahat O, Roblee R, Coachman C, Heymann HO. Evolution of aesthetic dentistry. J Dent Res. 2019;98(12):1294–304. https://doi.org/10.1177/0022034519875450.
2. Ye H, Wang K-P, Liu Y, Liu Y, Zhou Y. Four-dimensional digital prediction of the esthetic outcome and digital implementation for rehabilitation in the esthetic zone. J Prosthet Dent. 2020;123(4):557–63. https://doi.org/10.1016/j.prosdent.2019.04.007.
3. Shah P, Louca C, Patel R, Fine P, Blizard R, Leung A. Investigating working practices of dentists on shade taking: Evidence based good practice versus observed practice. J Dent. 2020;97:103341. https://doi.org/10.1016/j.jdent.2020.103341
4. Ahn J-S, Lee Y-K. Color distribution of a shade guide in the value, chroma, and hue scale. J Prosthet Dent. 2008;100(1):18–28. https://doi.org/10.1016/S0022-3913(08)60129-8.
5. Paravina RD. Performance assessment of dental shade guides. J Dent. 2009;37(Suppl 1):e15–20. https://doi.org/10.1016/j.jdent.2009.02.005.
6. Brook AH, Smith RN, Lath DJ. The clinical measurement of tooth colour and stain. Int Dent J. 2007;57(5):324–30. https://doi.org/10.1111/j.1875-595X.2007.tb00141.x.
7. Ortolan SM, Persic S, Celebic A, Mehulic K. Comparison of time consumption and color matching results of different dental occupational groups. Int J Prosthodont. 2013;26(5):478–86. https://doi.org/10.11607/ijp.3398.
8. Pecho OE, Pérez MM, Ghinea R, Della BA. Lightness, chroma and hue differences on visual shade matching. Dent Mater. 2016;32(11):1362–73. https://doi.org/10.1016/j.dental.2016.08.218.
9. Yılmaz B, Irmak Ö, Yaman BC. Outcomes of visual tooth shade selection performed by operators with different experience. J Esthet Restor Dent. 2019;31(5):500–7. https://doi.org/10.1111/jerd.12507.
10. Chen H, Huang J, Dong X, Qian J, He J, Qu X, Lu E. A systematic review of visual and instrumental measurements for tooth shade matching. Quintessence Int. 2012;43(8):649–59. PMID: 23034418.
11. Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Review of clinical and research aspects. J Dent. 2010;38:e2–16. https://doi.org/10.1016/j.jdent.2010.07.001.
12. Samra APB, Moro MG, Mazur RF, Vieira S, De Souza EM, Freire A, Rached RN. Performance of dental students in shade matching: Impact of training. J Esthet Restor Dent. 2017;29(2):E24–E32. https://doi.org/10.1111/jerd.12287.
13. Seghi RR, Johnston WM, O'Brien WJ. Performance assessment of colorimetric devices on dental porcelains. J Dent Res. 1989;68(12):1755–9. https://doi.org/10.1177/00220345890680120701.
14. Joiner A. Tooth colour: a review of the literature. J Dent. 2004;32(Suppl 1):3–12. https://doi.org/10.1016/j.jdent.2003.10.013.
15. Ristic I, Stankovic S, Paravina RD. Influence of color education and training on shade matching skills. J Esthet Restor Dent. 2016;28(5):287–94. https://doi.org/10.1111/jerd.12209.
16. Clary JA, Ontiveros JC, Cron SG, Paravina RD. Influence of light source, polarization, education, and training on shade matching quality. J Prosthet Dent. 2016;116(1):91–7. https://doi.org/10.1016/j.prosdent.2015.12.008.
17. Hammad IA. Intrarater repeatability of shade selections with two shade guides. J Prosthet Dent. 2003;89(1):50–3. https://doi.org/10.1067/mpr.2003.60.
18. Joiner A, Luo W. Tooth colour and whiteness: A review. J Dent. 2017;67:S3–10. https://doi.org/10.1016/j.jdent.2017.09.006.
19. Tam W-K, Lee H-J. Accurate shade image matching by using a smartphone camera. J Prosthodont Res. 2017;61(2):168–76. https://doi.org/10.1016/j.jpor.2016.07.004.
20. Rutkūnas V, Dirsė J, Bilius V. Accuracy of an intraoral digital scanner in tooth color determination. J Prosthet Dent. 2020;123(2):322–9. https://doi.org/10.1016/j.prosdent.2018.12.020.
21. Witkowski S, Yajima N-D, Wolkewitz M, Strub JR. Reliability of shade selection using an intraoral spectrophotometer. Clin Oral Investig. 2012;16(3):945–9. https://doi.org/10.1007/s00784-011-0590-3.
22. Johnston WM, Hesse NS, Davis BK, Seghi RR. Analysis of edge-losses in reflectance measurements of pigmented maxillofacial elastomer. J Dent Res. 1996;75(2):752–60. https://doi.org/10.1177/00220345960750020401.
23. Bolt RA, Bosch JJ, Coops JC. Influence of window size in small-window colour measurement, particularly of teeth. Phys Med Biol. 1994;39(7):1133–42. https://doi.org/10.1088/0031-9155/39/7/006.
24. Ebeid K, Sabet A, Della BA. Accuracy and repeatability of different intraoral scanners on shade determination. J Esthet Restor Dent. 2020. https://doi.org/10.1111/jerd.12687.

25. Schaefer O, Decker M, Wittstock F, Kuepper H, Guentsch A. Impact of digital impression techniques on the adaption of ceramic partial crowns in vitro. J Dent. 2014;42(6):677–83. https://doi.org/10.1016/j.jdent.2014.01.016.
26. Park J-M. Comparative analysis on reproducibility among 5 intraoral scanners: Sectional analysis according to restoration type and preparation outline form. J Adv Prosthodont. 2016;8(5):354–62. https://doi.org/10.4047/jap.2016.8.5.354.
27. Logozzo S, Zanetti EM, Franceschini G, Kilpelä A, Mäkynen A. Recent advances in dental optics – Part I: 3D intraoral scanners for restorative dentistry. Opt Laser Eng. 2014;54:203–21. https://doi.org/10.1016/j.optlaseng.2013.07.017.
28. Revilla-León M, Jiang P, Sadeghpour M, Piedra-Cascón W, Zandinejad A, Özcan M, Krishnamurthy V. Intraoral digital scans—Part 1: Influence of ambient scanning light conditions on the accuracy (trueness and precision) of different intraoral scanners. J Prosthet Dent. 2020;124(3):372–8. https://doi.org/10.1016/j.prosdent.2019.06.003.
29. Mehl A, Bosch G, Fischer C, Ender A. In vivo tooth-color measurement with a new 3D intraoral scanning system in comparison to conventional digital and visual color determination methods. Int J Comput Dent. 2017;20(4):343–61. PMID: 29292410.
30. Yoon HI, Bae JW, Park JM, Chun YS, Kim MA, Kim M. A study on possibility of clinical application for color measurements of shade guides using an intraoral digital scanner. J Prosthodont. 2018;27(7):670–5. https://doi.org/10.1111/jopr.12559.
31. Hampé-Kautz V, Salehi A, Senger B, Etienne O. A comparative in vivo study of new shade matching procedures. Int J Comput Dent. 2020;23(4):317–323. PMID: 33491927.
32. Liberato WF, Barreto IC, Costa PP, De Almeida CC, Pimentel W, Tiossi R. A comparison between visual, intraoral scanner, and spectrophotometer shade matching: A clinical study. J Prosthet Dent. 2019;121(2):271–5. https://doi.org/10.1016/j.prosdent.2018.05.004.
33. Revilla-León M, Methani MM, Öezcan M. Impact of the ambient light illuminance conditions on the shade matching capabilities of an intraoral scanner. J Esthet Restor Dent. 2020. https://doi.org/10.1111/jerd.12662.
34. Brandt J, Nelson S, Lauer H-C, Hehn UV, Brandt S. In vivo study for tooth colour determination—visual versus digital. Clin Oral Investig. 2017;21(9):2863–71. https://doi.org/10.1007/s00784-017-2088-0.
35. European Committee for Standardization. EN12464–1:2021. Light and lighting - Lighting of work places - Part 1: Indoor work places. Brussels: European Committee for Standardization; 2021.
36. Hugo B, Witzel T, Klaiber B. Comparison of in vivo visual and computer-aided tooth shade determination. Clin Oral Investig. 2005;9(4):244–50. https://doi.org/10.1007/s00784-005-0014-3.
37. International Standardization Organization. ISO/TR 28642. Technical Report(E): Dentistry –Guidance on Color Measurements. Geneva: ISO; 2016.
38. Suliman S, Sulaiman TA, Olafsson VG, Delgado AJ, Donovan TE, Heymann HO. Effect of time on tooth dehydration and rehydration. J Esthet Restor Dent. 2019;31(2):118–23. https://doi.org/10.1111/jerd.12461.
39. Burki Z, Watkins S, Wilson R, Fenlon M. A randomised controlled trial to investigate the effects of dehydration on tooth colour. J Dent. 2012;41(3):250–7. https://doi.org/10.1016/j.jdent.2012.11.009.
40. Öngül D, Şermet B, Balkaya MC. Visual and instrumental evaluation of color match ability of 2 shade guides on a ceramic system. J Prosthet Dent. 2012. https://doi.org/10.1016/S0022-3913(12)60102-4.
41. Liu Y, Zhang R, Ye H, Wang S, Wang KP, Liu Y, Zhou Y. The development of a 3D colour reproduction system of digital impressions with an intraoral scanner and a 3D printer: a preliminary study. Sci Rep. 2019;9(1):20052. https://doi.org/10.1038/s41598-019-56624-3.
42. Igiel C, Lehmann KM, Ghinea R, Weyhrauch M, Hangx Y, Scheller H, et al. Reliability of visual and instrumental color matching. J Esthet Restor Dent. 2017;29(5):303–8. https://doi.org/10.1111/jerd.12321.
43. Özat PB, Tuncel İ, Eroğlu E. Repeatability and reliability of human eye in visual shade selection. J Oral Rehabil. 2013;40(12):958–64. https://doi.org/10.1111/joor.12103.
44. Lagouvardos PE, Fougia AG, Diamantopoulou SA, Polyzois GL. Repeatability and interdevice reliability of two portable color selection devices in matching and measuring tooth color. J Prosthet Dent. 2009;101(1):40–5. https://doi.org/10.1016/S0022-3913(08)60289-9.
45. Almufleh B, Emami E, Al-Khateeb A, Del Monte S, Tamimi F. Tooth shade preferences among the general public. J Prosthodont. 2020;29(7):564–72. https://doi.org/10.1111/jopr.13213.
46. Sproull RC. Color matching in dentistry. Part II. Practical applications of the organization of color. J Prosthet Dent. 2001;86(5):458–64. https://doi.org/10.1067/mpr.2001.119828.
47. Hunt RWG, Pointer MR. Measuring Colour. 4th ed. GB: Wiley; 2011.
48. Sproull RC. Color matching in dentistry. Part I. The three-dimensional nature of color. J Prosthet Dent. 2001;86(5):453–7. https://doi.org/10.1067/mpr.2001.119827.
49. Berns RS, Billmeyer FW Jr. Development of the 1929 munsell book of color: a historical review. Color Res Appl. 1985;10(4):246–50. https://doi.org/10.1002/col.5080100415.
50. Lehmann KM, Devigus A, Igiel C, Weyhrauch M, Schmidtmann I, Wentaschek S, Scheller H. Are dental color measuring devices CIE compliant? Eur J Esthet Dent. 2012;7(3):324–33. PMID: 22908079.
51. Commission Internationale de l'Éclairage. CIE Technical Report: Colorimetry. CIE Pub No. 15.3. Vienna, Austria: CIE Central Bureau; 2004.
52. Johnston WM. Color measurement in dentistry. J Dent. 2009;37(1):e2–6. https://doi.org/10.1016/j.jdent.2009.03.011.
53. Hasegawa A, Ikeda I, Kawaguchi S. Color and translucency of in vivo natural central incisors. J Prosthet Dent. 2000;83(4):418–23. https://doi.org/10.1016/S0022-3913(00)70036-9.
54. Di Murro B, Gallusi G, Nardi R, Libonati A, Angotti V, Campanella V. The relationship of tooth shade and skin tone and its influence on the smile attractiveness. J Esthet Restor Dent. 2020;32(1):57–63. https://doi.org/10.1111/jerd.12543.
55. Koseoglu M, Bayindir F. Effects of gingival margin asymmetries on the smile esthetic perception of dental professionals and lay people. J Esthet Restor Dent. 2020;32(5):480–6. https://doi.org/10.1111/jerd.12595.
56. Sybaite J, Sharma P, Fine P, Blizard R, Leung A. The Influence of Varying Gingival Display of Maxillary Anterior Teeth on the Perceptions of Smile Aesthetics. J Dent. 2020;103: 103504. https://doi.org/10.1016/j.jdent.2020.103504.