THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Color perceptibility and validity of silicon carbide–based protective coatings for dental ceramics

Chaker Fares, MS,[a] Randy Elhassani, BS,[b] Fan Ren, PhD,[c] Alexandra R. Cabrera, BS,[d] Ingrid Chai, BS,[e] Dan Neal, MS,[f] Shu-Min Hsu, PhD,[g] and Josephine F. Esquivel-Upshaw, DMD, MS, MS-CI, FACD[h]

ABSTRACT

Statement of problem. A silicon carbide (SiC) protective coating has been developed for dental ceramics, but whether the coated ceramics can match the classical VITA shades is unclear.

Purpose. The purpose of this observational in vitro study was to evaluate the color adaptability of SiC-coated dental ceramics by testing the hypotheses that SiC-coated disks can be fabricated to match standard tooth shades and have a perceptible color match rate of at least 50% for disks with a color difference (ΔE)<2.0. The effects of ΔE, shade hue, shade value, observer sex, years of experience, profession, and shade guide orientation on color perception were studied.

Material and methods. SiC-coated disks were fabricated to color match (ΔE_{ab}<3.3) all 16 VITA classical shades. Uncoated disks of each VITA shade were used as the reference materials to determine whether the SiC-coated disks were color matched to the classical VITA shade guide. Three ΔE formulas (76, 94, and 2000) were applied and compared. Participants (N=120) with an average of 22 years of experience included dental school students, dental faculty members, and dental assistants. Pseudoisochromatic plate and the Farnsworth D-15 Panel test for assessing color deficiency and color blindness were administered. Participants then attempted to match SiC-coated disks to standard shade guides arranged by value or hue. All spectrophotometer readings and color matching were conducted in a light booth with standardized daylight illumination. Statistical analysis used the Fisher's exact test to determine factors associated with improved matching performance (α=.05).

Results. A significant difference in color match rate was found between disks with ΔE<2.0 (63.9%) and $\Delta E \geq 2.0$ (41.7%) (*P*<.001). Arranging shade by value (72.2%) instead of hue (67.2%) produced better color matching (*P*<.001). Sex (*P*=.430), profession (*P*=.708), and years of experience (*P*=.902) had no significant influence on color matching.

Conclusions. SiC-coated disks were successfully fabricated to match all VITA classical shades, and clinical visual color matching results confirmed that ΔE was a useful metric in optimizing color matching for the SiC-coated dental ceramics. (J Prosthet Dent 2022;127:918-24)

Glass-based ceramic materials have been used extensively for fixed dental prostheses (FDPs)[1-3] and must be durable, biocompatible, and esthetically acceptable. Chemical and mechanical wear cause a roughened ceramic surface that can contribute to considerable wear on the opposing tooth and promote plaque or biofilm accumulation.[4-6] Additionally, increased wear on the ceramic surface reduces flexural strength through glass-phase degradation and yields an accelerated loss of surface structure, increasing the risk of chipping.[5,7] These failure mechanisms can severely reduce the lifetime of ceramic restorations and damage nearby oral structures. To reduce chipping failures and surface roughening, monolithic zirconia has

Supported by NIH-NIDCR Grant R01 DE025001 and the University of Florida College of Dentistry Office of Research.
[a]Graduate student, Department of Chemical Engineering, University of Florida College of Engineering, Gainesville, Fla.
[b]Undergraduate student, Department of Chemical Engineering, University of Florida College of Engineering, Gainesville, Fla.
[c]Distinguished Professor, Department of Chemical Engineering, University of Florida College of Engineering, Gainesville, Fla.
[d]Dental student, Division of Prosthodontics, Restorative Dental Sciences, University of Florida College of Dentistry, Gainesville, Fla.
[e]Undergraduate student, Department of Chemistry and Biochemistry, University of California San Diego, San Diego, Calif.
[f]Statistician, Department of Surgery, University of Florida College of Medicine, Gainesville, Fla.
[g]Research Associate, Division of Prosthodontics, Department of Restorative Dental Sciences, University of Florida College of Dentistry, Gainesville, Fla.
[h]Professor, Division of Prosthodontics, Department of Restorative Dental Sciences, University of Florida College of Dentistry, Gainesville, Fla.

Clinical Implications

When depositing silicon carbide as a protective coating for dental ceramics, the coating's thickness can be varied to enable a prosthesis to match any color within the VITA classical shade guide.

been preferred over veneered ceramics because of this material's high flexural strength, toughness, and hardness.[8,9] Despite advantages, sintering monolithic zirconia at high temperatures causes oxygen vacancies to form, which results in material discoloration and poor shade match.[10,11]

An alternative method for improving dental ceramics is to coat existing ceramics with a more durable material to improve mechanical and chemical properties. Silicon carbide (SiC) coating is promising because it imparts corrosion resistance and has excellent mechanical properties as compared with standard silicon-based nitride or oxide coatings.[12-15] However, although the authors are unaware of research on the biocompatibility of SiC-based coatings for dental applications, the biocompatibility of SiC for other applications has been demonstrated.[16-19]

In addition to the chemical and mechanical properties, a realistic appearance is essential for dental prostheses. Teeth are composed of stratiform semitranslucent layers of dentin and enamel that reflect, absorb, refract, or transmit all or part of incident light, through which the quality of a tooth's color is produced.[2,20] Color matching in dentistry is routinely conducted by using dental shade guides and is dependent on individual color perception. A person's ability to perceive color and choose the proper shade can also be problematic. In 1970, Culpepper et al[21] reported on the unreliability and imprecision of visual shade selection.[22] Color discrimination varies among individuals, and visual color selection depends on factors such as size, position, shape, surrounding illumination, and background color.[23-25] The multiple subjective variables within visual color determination make an objective method desirable. Color measurement instruments have the potential to eliminate some of the subjective variables within shade selection,[2] with many advancements in technology developed within the past 20 years to minimize subjectivity.[26] The accuracy and practicality of these instruments have been evaluated,[27-33] and 2 studies have reported low agreement between instrument-based shade determination and visual shade determination.[31,32] A comparison of visual perception and instrumental shade determination should be performed for new dental materials. By comparing visual and instrumental shade matching, the clinical acceptability of the new material and how this compares with those currently available can be determined. For SiC coating, previous data demonstrated that the thickness of SiC can be varied to match any color within the VITA classical shade guide.[34]

The International Commission on Illumination (CIE) has made refinements over the past few decades to the original color difference formula (ΔE 76). The ΔE 76 formula measures color difference by taking the variation between each specimen's lightness (L*), red-green (a*), and blue-yellow (b*) value in CIELab color space. The ΔE 94, followed by the most recent version, the ΔE 2000, incorporated various correction and weighting factors to account for different materials, saturation, and weighting.[35,36] To consider a coated disk to visually match the Vita shade guide, a ΔE_{ab} value less than 3.3 is required.[37] The 3 ΔE formulas are shown below[38]:

$$\Delta E_{76} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

$$\Delta E_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2} \quad (2)$$

$$\Delta E_{2000} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}} \quad (3)$$

where L^* is the lightness, a^* is the green/red color component, b^* is the yellow/blue color component, and ΔL^*, Δa^* and Δb^* indicate differences in L^*, a^* and b^* between 2 specimens. L′ is the transformed lightness value, C′ is the transformed chroma value, H′ is the transformed hue value, and R_T is a rotation factor for chroma and hue. ΔL′, ΔC′, and ΔH′ indicate differences in lightness, chroma, and hue between a standard and a coated specimen. $K_L S_L$, $K_C S_C$, and $K_H S_H$ are correction factors for lightness, chroma, and hue, respectively. Hue (H) is defined as the attribute of color perception by means of which an object is judged to be green, yellow purple, red, blue, and so forth.[39] Value is defined as perception by which light objects are distinguished from dark objects.[39] Other factors such as years of experience, sex, and specialty of examiners have been reported to have both a significant[40] and nonsignificant effect[41-43] on visual perception.

To further develop SiC-based coatings for dental applications, the efficacy of instrument-based color matching as with visual shade selection must be established. The research hypotheses for the present study were that SiC-coated disks can be fabricated to match standard tooth shades and have a perceptible match rate of at least 50% for disks with a ΔE<2.0; that shade

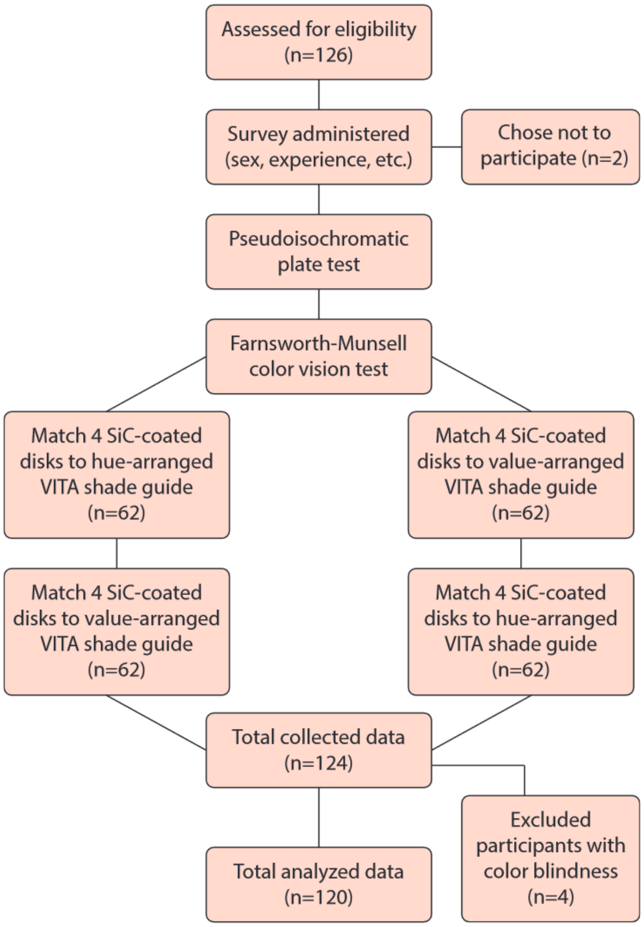

Figure 1. Clinical procedure flow diagram.

matching is better achieved with value rather than hue in SiC-coated disks; and that a ΔE<2.0 will predict higher shade perception in SiC-coated disks. The ΔE threshold was chosen based on previous color matching studies on dental ceramics.[37] Additionally, the effects of sex, years of experience, profession, shade hue, and shade value on the color perceptibility of SiC-coated disks were determined.

MATERIAL AND METHODS

SiO_2 and SiC films were deposited by using a plasma-enhanced chemical vapor deposition (PECVD) system (PlasmaTherm 790; Plasma-Therm) at 573.15 K. The gas precursors used were silane and nitrous oxide for SiO_2, whereas methane and silane were used to deposit SiC. The deposition pressure was 120 Pa for SiO_2 and 147 Pa for SiC. The deposition rate was 5.67 Å/s for SiO_2 and 2.75 Å/s for SiC. The self-bias voltage was between 0 and 4 V for both films. The reactor geometry was a classic parallel-plate configuration with a shower head and a 305-mm-diameter high-temperature substrate platen. Additional deposition information can be found in a previous report.[34]

To investigate the capability of the SiO_2 and SiC coatings for VITA color shades, glass-ceramic (IPS e.max ZirPress; Ivoclar AG) disks (Ø12×2 mm) were used as specimens to coat different thicknesses of SiO_2 and SiC films. Before the coating process, the disks were cleaned with acetone in an ultrasonic bath, rinsed with isopropyl alcohol, and dried with compressed nitrogen. SiC-coated disks were fabricated to color match ($\Delta E_{ab}<3.3$) all 16 VITA classical shades. Uncoated disks of each VITA shade were used as the reference. A spectrophotometer (Chroma Meter CR-300; Konica Minolta) was used to determine the color difference between specimens. The variations of 3 ΔE formulas (76, 94, and 2000) were compared in this study.

Institutional review board (IRB) approval was obtained for this clinical study. A prerequisite to participate in the clinical study was being involved in dentistry in areas such as being a student, researcher, clinical faculty, graduate resident, or dental assistant. The enrollment, eligibility diagram, and clinical procedures used are shown in Figure 1. Written consent was obtained in the laboratory where the testing took place. A brief questionnaire requested information including age, observer sex, years of dental experience, and corrective eyewear use. A pseudoisochromatic plate test and the Farnsworth D-15 panel test were administered to assess chromatic perception in the red-green and blue-yellow axes. Data from participants who tested positive for color-vision deficiency were collected but not included in the final statistical data. One hundred twenty participants were recruited after a pilot study, and power analysis was performed. The effects of hue, value, sex, years of experience, profession, and shade guide orientation on color matching were investigated.

All spectrophotometer readings and color matching were conducted in a light booth with standardized daylight (D65) illumination (SpectraLight; Macbeth) against a neutral gray interior known as Munsell N-7. The booth was the sole light influence in the testing room.

Each participant was tested by using a computer randomized combination of shades for both the hue and value test. Although each participant had a random combination, by the end of the study, each shade had been tested an equal number of times.

This study was administered in 2 separate phases and was conducted as a single blind trial in which the participant was unaware of the color scheme. In the first phase, the participant was given a single coated disk to match a shade guide arranged in order of hue and in the second phase, by value. Each participant was given 4 random shades to match for each phase.

Statistical analysis was performed by using a statistical software package (R, v3.6.1; The R Foundation for Statistical Computing). Binomial tests were used to

Shade	A1	A2	A3	A3.5	A4	B1	B2	B3	B4	C1	C2	C3	C4	D2	D3	D4
Substrate	BL3	A1	A1	A1	A3.5	BL1	B1	A1	B3	B1	B1	C2	C4	B1	B2	B2
SiC (nm)	140	155	180	325	300	125	145	170	140	100	250	150	100	110	80	150
ΔE 76	2.91	4.24	3.48	2.73	3.63	3.55	1.17	6.02	1.22	3.38	4.16	3.57	2.14	2.52	3.61	3.63
ΔE 94	1.68	3.16	1.92	2.22	2.99	2.92	0.89	2.97	0.66	3.34	3.38	2.05	1.50	1.42	2.00	1.97
ΔE 2000	1.64	2.63	1.78	2.10	2.61	2.97	0.89	2.83	0.74	2.09	2.82	1.96	1.85	1.55	1.95	2.07

Figure 2. Top row of disks uncoated ZirPress disks for each classical VITA shade. Bottom row of disks SiC-coated ZirPress disks fabricated to color match VITA standards. Table lists substrate shade, SiC coating thickness, and corresponding ΔE of each coated disk compared with reference. 20-nm SiO_2 deposited before SiC deposition.

determine whether the overall match rate, the match rates for differing values of ΔE, and the match rates for various shade subgroups differed significantly from a benchmark or hypothesized value. The Fisher's exact test was used to compare the matching performance among participant groups (α=.05).

RESULTS

The SiC-coated disks used for the clinical study and their respective SiC thickness, ΔE values, and the shade of the substrate used are shown in Figure 2. In this study, a ΔE_{2000} value less than 3.3 was required to consider a SiC-coated disk to be a match to the standard shade guide.[37] A total of 70 women and 50 men participated. The average age for faculty was 47 years; resident 32 years; staff 40 years; and student 25 years. The years of experience in the dental field for faculty ranged from 3 years to 55 years, with an average of 22 years. The participants had a mean of 4.05 correct matches of the 8 coated disks they were randomly assigned (50.6% correct), with a range from 1 to 8 correct matches.

The number of incorrect selections along with the frequency of incorrect selections by the participants is shown in Figure 3. Within each respective hue group, the middle shades including A2, A3, B2, B3, C2, C3, and D3 were incorrectly matched more frequently than the lightest or darkest shades of each respective hue, creating a bimodal distribution. Table 1 shows the correct match rate of SiC-coated disks compared with a standard set using a hue or value arranged shade guide. Additionally, Table 1 details the match rate as a function of ΔE and compares the match rates between the lightest and darkest shades, middles shades, and overall group.

Using a hue-arranged shade guide, participants correctly matched 121 out of 180 (67.2%) of SiC-coated disks with a ΔE_{2000} value less than 2 while correctly matching only 143 of 300 (47.7%) of disks with a $\Delta E \geq 2.0$. This trend did not apply to all disks and will be evaluated further in the discussion section. Using a value-arranged shade guide, participants correctly matched 130 of 180 (72.2%) SiC-coated disks with a ΔE_{2000} value less than 2 while only correctly matching 174 of 300 (58%) disks with a $\Delta E \geq 2$.

Figure 4A shows that the 86% match rate of the lightest shades (A1, B1) and darkest shades (A4, B4, C4) was significantly higher than the average match rate of 51% (P<.001). Figure 4B shows that participants correctly matched 63.9% of disks with $\Delta E<2$, significantly better than the 41.7% match rate for disks with $\Delta E \geq 2$ (P<.001) and significantly better than 50% (P<.001). Observer sex (P=.430), profession (P=.708), and years of experience (P=.902) had no significant influence on color matching results.

DISCUSSION

The hypotheses that SiC-coated disks can be fabricated to match classical VITA shades and have a perceptible match rate of at least 50% for disks with a $\Delta E<2.0$ and that a $\Delta E<2.0$ will predict higher shade perception in SiC-coated disks were accepted. The actual color match rate was 63.9%, and a significant difference in match rates was found between disks with $\Delta E<2.0$ and $\Delta E \geq 2$ (P<.001). The hypothesis that arranging shade by value (72.2%) instead of hue (67.2%) produces better color matching was also accepted (P<.001). This study determined that SiC-coated dental ceramics can be fabricated to match any classical VITA shade. The overall color match rate when observers visually compared SiC-coated disks with classical VITA shade guides was 50.6%. Of the 120 observers, 3 had no mismatches and received a perfect score. The correct match rate of 50.6% was consistent with previous color matching studies focusing on dental ceramics.[21,32] The match rate in this study and those reported previously are the result of inconsistencies in color perception among individuals and are also

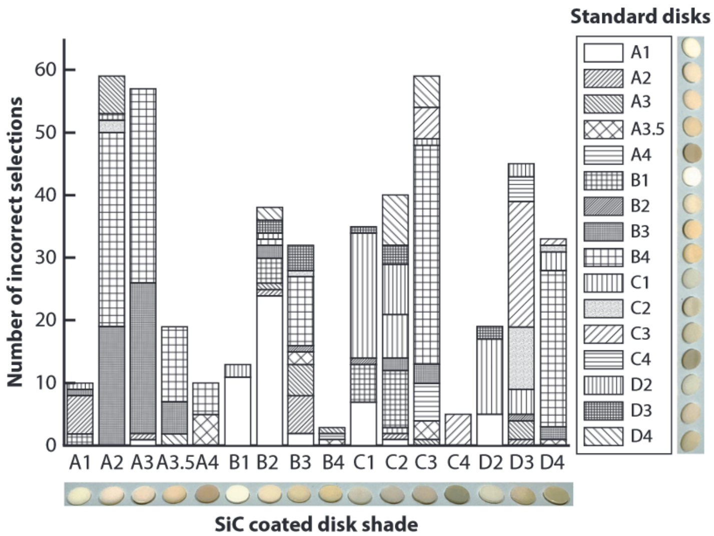

Figure 3. Distribution of incorrect shade selections made by observers during study.

because of the various complexities in color matching dental ceramics. Okubo et al[32] tested the ability of observers to match individual tabs of Vita Lumin shade guides to another Vita Lumin shade guide and reported that even when comparing the exact same materials from the same manufacturer, visual matching from 31 observers yielded an average match rate of 48%.

When comparing the results from the different ΔE formulas, the ΔE_{2000} formula demonstrating the lowest ΔE values for 11 of 16 disks when compared with references. Despite these lower values, the choice in ΔE formula primarily affected the magnitude of the color difference and was determined not to be a leading factor in the color optimization process for the studied material system. Overall, the use of a spectrophotometer to color match SiC-coated dental ceramics to standards achieved a similar visual match rate to that reported previously,[21,32] indicating that color measurement instruments can be a useful tool in color determination for SiC-coated dental ceramics in conjunction with visual shade matching.

As shown in Figure 3, the middle shades of each hue (A2, A3, B2, B3, C2, C3, and D3) were incorrectly matched more frequently than the lightest or darkest shades of each respective hue. This trend agrees with previous reports[21,32] and is likely because the lightest and darkest shades are easier to distinguish and there are more shade tab choices in the middle shade range, which increases the likelihood of an incorrect match. Furthermore, the larger number of correct matches for the highest and lower members of each hue group results in a bimodal distribution. This distribution is shown in the averages in Table 1 and highlights that matching performance differs greatly in 2 separate ranges, those at the extremes of each hue and those in between.

Another source of incorrect matches was that several fabricated SiC-coated disks achieved ΔE_{2000} values less

Table 1. Visual matching results comparing SiC-coated disks with reference disks

Shade	ΔE 2000	Match % Using Hue Arranged Shade Guide	Match % Using Value Arranged Shade Guide	Overall Match %
A1	1.64	86.7	80.0	83.4
A2	2.63	0.00	3.30	1.70
A3	1.78	3.30	6.70	5.00
A3.5	2.10	63.3	73.3	68.3
A4	2.61	76.7	86.7	81.7
B1	2.97	83.3	73.3	78.3
B2	0.89	26.7	46.7	36.7
B3	2.83	46.7	46.7	46.7
B4	0.74	100	90.0	95.0
C1	2.09	33.3	50.0	41.7
C2	2.82	30.0	63.3	46.7
C3	1.96	6.70	10.0	8.40
C4	1.85	100	83.3	91.7
D2	1.55	66.7	70.0	68.3
D3	1.95	26.7	23.3	25.0
D4	2.07	50.0	40.0	45.0
All shades		50.0	51.2	50.6
Shades with ΔE<2		63.9	62.8	63.4
Shades with ΔE≥2		41.7	44.3	43.0
Lightest/darkest shades (A1, B1, A4, B4, C4)		82.7	89.3	86.0
Middle shades (A2, A3, B2, B3, C2, C3, D3)		20.0	28.6	24.3

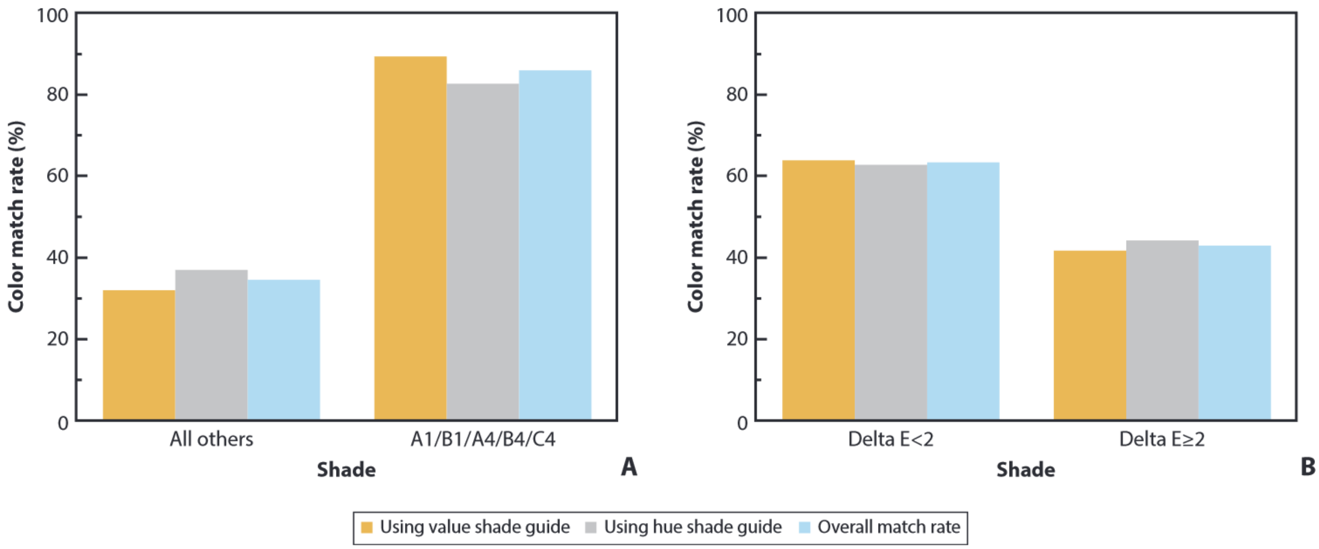

Figure 4. Correct match rate. A, As function of shade value. B, As function of ΔE.

than 3.3 between multiple classical VITA shades. For example, the SiC-coated disk used to match the A3 standard shade had a ΔE value of 1.78 between A3 but also had a ΔE value of 3.15 between the B3 standard shade. These small variations in ΔE and the potential for multiple matches further highlight the difficulty of visual color matching.

To further emphasize the effect of shade hue on match rate, Figure 4A shows the percentage of correct visual matches of the lightest and darkest shades in the shade guide (A1, B1, B4, and C4) compared with the average visual match rate in the clinical study. The average visual match rate for the A1, B1, A4, C4, and B4 shades was approximately 86%, whereas the visual match rate for the rest of the shades was 34.5%.

The present study demonstrated that SiC-coated disks with a ΔE_{2000}<2 had a better match rate in general, but this was not always the case. For example, the SiC-coated disk fabricated to match A3 had ΔE_{2000}= 1.78 but had a visual match rate of 5%. These exceptions to the general trend that coated disks with lower ΔE values achieved higher match rates could be because of the unavoidable difficulty and variability of visual shade matching. The SiC-coated disks that had ΔE_{2000}<2 but achieved visual match rates below 60% were the following shades: A3, B2, B3, C3, and D3. All these shades are in the middle of each hue group, which was consistent with previous reports and was expected.[21,32]

The average visual color match rates for faculty was 49.6%, residents 48.3%, staff 54%, and students 51.75%. These results show no significant effect of profession on visual match rate (*P*=.430), which agrees with previous reports.[41] A different study showed that prosthodontists had better intrarater repeatability for shade selection when compared with general practitioners.[40] Faculty participants in this study completed the visual matching at an observed faster rate than the dental students and staff. This speed could have resulted in additional errors for the dental faculty that could not be quantified by the recorded data. Additionally, the overall match rate for women was 52.8% compared with 47.8% for men. Although women had a slight edge when using both the hue and value arranged shade guides, this difference was not statistically significant (*P*=.708). Many dentistry-related studies have reported similar evidence on the nonsignificance of sex on shade matching.[41-43] Like observer sex, years of experience had no significant effect on the results of color matching SiC-coated disks to standard shades (*P*=.902), which was consistent with previous reports.[41,42] Hammad et al[40] reported that among 614 color normal participants, students with little or no experience in shade matching achieved the same results as experienced dental professionals.

Color replication and the quantification of color have proven to be complex challenges in dentistry. The main purpose of this study was not to simply present additional evidence on color matching but rather to show that SiC-coated dental ceramics can be a viable option in prosthodontics. These coated ceramics will inevitably yield some of the same challenges in color replication as currently used dental materials but, hopefully, with the added benefit of durability and chemical resistiveness. Limitations of this study included that color matching was conducted using planar disks at a relatively fixed viewing angle similar to previous color perception studies. Future work should include perceptibility studies on nonplanar SiC-coated dental ceramics with the addition of wear, corrosion resistance, and biocompatibility analyses.

CONCLUSIONS

Based on the findings of this observational in vitro study, the following conclusions were drawn:

1. SiC-coated disks were successfully fabricated to match all VITA classical shades, and clinical visual color matching results confirmed that ΔE was a useful metric in optimizing color matching for the SiC-coated dental ceramics.
2. The overall match rate of the SiC-coated disks to classical VITA shades was 50.6% and was consistent with previous color matching studies on dental ceramics.
3. Participants correctly matched 63.9% of disks with $\Delta E<2$, significantly better than the 41.7% match rate for disks with $\Delta E\geq 2$ ($P<.001$) and significantly better than 50% ($P<.001$).
4. Observer sex, profession, and years of experience had no significant effect on the color matching results ($P>.05$).

REFERENCES

1. Sailer I, Makarov NA, Thoma DS, Zwahlen M, Pjetursson BE. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: single crowns (SCs). Dent Mater 2015;31:603-23.
2. A. Da Silva N.Morimoto, Gas flow simulation in a PECVD reactor. In Proceedings of the 2002 International Conference on Computational Nanoscience and Nanotechnology, San Juan, Puerto Rico, 22–25 April 2002.
3. Tian T, Tsoi JK-H, Matinlinna JP, Burrow MF. Aspects of bonding between resin luting cements and glass ceramic materials. Dent Mater 2014;30:e147-62.
4. Anusavice KJ, Kakar K, Ferree N. Which mechanical and physical testing methods are relevant for predicting the clinical performance of ceramic-based dental prostheses? Clin Oral Implants Res 2007;18:218-31.
5. Esquivel-Upshaw JF, Dieng FY, Clark AE, Neal D, Anusavice KJ. Surface degradation of dental ceramics as a function of environmental pH. J Dent Res 2013;92:467-71.
6. Sailer I, Hammerle C. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up. Int J Prosthodont 2009;22:553-60.
7. Esquivel-Upshaw JF, Ren F, Hsu SM, Dieng FY, Neal D, Clark AE. Novel testing for corrosion of glass-ceramics for dental applications. J Dent Res 2018;97:296-302.
8. Nakamura K, Harada A, Inagaki R, Kanno T, Niwano Y, Milleding P, et al. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. Acta Odontol Scand 2015;73:602-8.
9. Sripetchdanond J, Leevailoj C. Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: an in vitro study. J Prosthet Dent 2014;112:1141-50.
10. Ebeid K, Wille S, Hamdy A, Salah T, El-Etreby A, Kern M. Effect of changes in sintering parameters on monolithic translucent zirconia. Dent Mater 2014;30:e419-24.
11. Langer J, Hoffmann MJ, Guillon O. Electric field-assisted sintering in comparison with the hot pressing of yttria-stabilized zirconia. J Am Ceram Soc 2011;94:24-31.
12. Flannery AF, Mourlas NJ, Storment CW, Tsai S, Tan SH, Heck J, et al. PECVD silicon carbide as a chemically resistant material for micromachined transducers. Sens Actuators A Phys 1998;70:48-55.
13. Ivashchenko VI, Turchi PEA, Shevchenko VI. Simulations of the mechanical properties of crystalline, nanocrystalline, and amorphous SiC and Si. Phys Rev B 2007;75:085209.
14. Sarro PM. Silicon carbide as a new MEMS technology. Sens Actuators A Phys 2000;82:210-8.
15. Müller G, Krötz G, Niemann E. SiC for sensors and high-temperature electronics. Sens Actuators A Phys 1994;43:259-68.
16. Amon M, Bolz A, Schaldach M. Improvement of stenting therapy with a silicon carbide coated tantalum stent. J Mater Sci Mater Med 1996;7:273-8.
17. Hashiguchi K, Hashimoto K. Mechanical and histological investigations on pressureless sintered SiC dental implants. Okajimas Folia Anat Jpn 1999;75:281-96.
18. Kotzar G, Freas M, Abel P, Fleischman A, Roy S, Zorman C, et al. Evaluation of MEMS materials of construction for implantable medical devices. Biomaterials 2002;23:2737-50.
19. Naji A, Harmand MF. Cytocompatibility of two coating materials, amorphous alumina and silicon carbide, using human differentiated cell cultures. Biomaterials 1991;12:690-4.
20. Abdullah W, Richards MW, Harrold Reed F, Ali Kanawati MM. A comparison of color matching of the vita easy shade system with visual methods using the vita 3D shade guide. Ann Arbor: West Virginia University; 2008. p. 1-19.
21. Culpepper WD. A comparative study of shade-matching procedures. J Prosthet Dent 1970;24:166-73.
22. Barna GJ, Taylor JW, King GE, Pelleu GB. The influence of selected light intensities on color perception within the color range of natural teeth. J Prosthet Dent 1981;46:450-3.
23. Dagg H, O'Connell B, Claffey N, Byrne D, Gorman C. The influence of some different factors on the accuracy of shade selection. J Oral Rehabil 2004;31:900-4.
24. Ragain JC, Johnston WM. Minimum color differences for discriminating mismatch between composite and tooth color. J Esthet Restor Dent 2001;13:41-8.
25. Brewer JD, Wee A, Seghi R. Advances in color matching. Dent Clin North Am 2004;48:341-58.
26. Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Review of clinical and research aspects. J Dent 2010;38 Suppl 2:e2-16.
27. Dancy K, Yaman P, Dennison JB, O'Brien WJ, Razzoog ME. Color measurements as quality criteria for clinical shade matching of porcelain crowns. J Esthet Restor Dent 2003;15:114-22.
28. Hugo B, Witzel T, Klaiber B. Comparison of in vivo visual and computer-aided tooth shade determination. Clin Oral Investig 2005;9:244-50.
29. Paul SJ, Peter A, Rodoni L, Pietrobon N. Conventional visual vs spectrophotometric shade taking for porcelain-fused-to-metal crowns: a clinical comparison. Int J Periodontics Restorative Dent 2004;24:222-31.
30. Dozić A, Kleverlaan CJ, El-Zohairy A, Feilzer AJ, Khashayar G. Performance of five commercially available tooth color-measuring devices. J Prosthodont 2007;16:93-100.
31. Klemetti E, Matela AM, Haag P, Kononen M. Shade selection performed by novice dental professionals and colorimeter. J Oral Rehabil 2006;33:31-5.
32. Okubo SR, Kanawati A, Richards MW, Childressd S. Evaluation of visual and instrument shade matching. J Prosthet Dent 1998;80:642-8.
33. Raigrodski AJ, Chiche GJ, Aoshima H, Spiekerman CF. Efficacy of a computerized shade selection system in matching the shade of anterior metal-ceramic crowns–a pilot study. Quintessence Int 2006;37:793-802.
34. Chen Z, Fares C, Elhassani R, Ren F, Kim M, Hsu S-M, et al. Demonstration of SiO2/SiC-based protective coating for dental ceramic prostheses. J Am Ceram Soc 2019;102:6591-9.
35. Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Res Appl 2005;30:21-30.
36. Luo MR, Cui G, Rigg B. The development of the CIE 2000 colour-difference formula: CIEDE2000. Color Res Appl 2001;26:340-50.
37. Vichi A, Louca C, Corciolani G, Ferrari M. Color related to ceramic and zirconia restorations: a review. Dent Mater 2011;27:97-108.
38. McLaren K. XIII-The development of the CIE 1976 (L* a* b*) uniform colour space and colour-difference formula. J Soc Dye Colour 2008;92:338-41.
39. Hunter R, Harold R. The measurement of appearance. 2nd ed. New York: John Wiley and Sons, Inc; 1987. p. 3-20.
40. Hammad IA. Intrarater repeatability of shade selections with two shade guides. J Prosthet Dent 2003;89:50-3.
41. Anusavice KJ, Shen C, Rawls HR. Phillips' science of dental materials. 10th ed. Philadelphia: Saunders; 2012. p. 42.
42. Curd FM, Jasinevicius TR, Graves A, Cox V, Sadan A. Comparison of the shade matching ability of dental students using two light sources. J Prosthet Dent 2006;96:391-6.
43. Winkler S, Boberick KG, Weitz KS, Datikashvili I, Wood R. Shade matching by dental students. J Oral Implantol 2006;32:256-8.

Corresponding author:
Dr Josephine F. Esquivel-Upshaw
Restorative Dental Sciences Department
University of Florida College of Dentistry
1395 Center Drive, Room D9-6
Gainesville, FL 32610
Email: jesquivel@dental.ufl.edu

Acknowledgments
The authors thank Ivoclar AG for providing ceramic materials.

https://doi.org/10.1016/j.prosdent.2020.10.023