INTRODUCTION

The final color of restorative dental materials is undoubtedly one of the most important parameters by which patients judge the quality of the restoration. Therefore, the color and relevant optical properties of restorative materials such as ceramics and composite resins have been investigated and described in numerous studies. However, most studies do not consider the effects of the temperature of materials, measuring instruments, and laboratory conditions on restorative materials.

In general, a change in an object’s temperature can change in its physical appearance, particularly its color. Reversible alternation of an object’s color with temperature variations is known as thermochromism, a phenomenon that has attracted much interest from scientists for quite some time. Compton and Fairchild and Grum investigated the thermochromism of twelve standard color tiles, which were developed as reference standards in colorimetry and spectrophotometry by The British Ceramic Research Association and The National Physical Laboratory. They reported that some standard color tiles showed significant thermochromic color change at a temperature change of 20ºC between the measurements at 25 and 45ºC. However, they concluded that the temperature change found in their study would not occur under normal laboratory conditions close to room temperature. On the other hand, intraoral temperature variation is significantly greater than room temperature variation, spanning from 4 to 55ºC or 60ºC. Therefore, the dental restorative materials are usually exposed to a wide range of temperatures.

However, no reports on thermochromic effects on dental restorative materials have apparently been published to date.

The purpose of this investigation was to clarify the thermochromism of restorative composite resins at typical intraoral temperatures. Five brands of restorative composite resins were used. The CIE $L^*a^*b^*$ color values were measured using a spectrophotometer at specimen temperatures of 4, 23, 37, 60, and 80ºC. The temperature dependence of the refractive index of the materials at 4–80ºC were also determined using a refractometer. The values of $L^*$ for all materials decreased, and those of $a^*$ and $b^*$ for most of the materials increased, with increasing temperature. The color difference ($\Delta E^*$) for all materials increased with increasing specimen temperatures. The refractive index of the A4 shade of the materials consistently decreased with increasing temperatures. Most of the materials exhibited perceptible thermochromism related to intraoral thermal conditions. Optical properties that change in response to temperature could help explain the thermochromism of materials.

Keywords: Composite resin, Thermochromism, Color change, Refractive index

MATERIALS AND METHODS

Materials

Five brands of light-cured restorative composite resins used in this study were included, and their manufacture, abbreviation, shade, and general chemical composition described by the manufacturer’s safety data sheet (SDS) were recorded (Table 1). Although shades A2, A4, B3, and C3 were selected for each restorative composite resin, shade B4 was substituted for B3 in the cases of CM and EL, and C4 was substituted for C3 in the cases of CM and VN. All composite resins used were translucent materials allowing light pass through but not transparent.

Color measurement

Color values of the materials, as measured by The Commission Internationale de l’Eclairage (CIE) $L^*a^*b^*$ color system in the reflectance mode were measured using a laboratory-grade spectrophotometer (CM-700d, Konica Minolta, Tokyo, Japan) with software for data analysis (Spectra Magic NX, Konica Minolta). The $L^*$ parameter describes the brightness coordinate, and $a^*$...
Table 1  Materials used

| Material          | Manufacturer       | Abbreviation | Shade       | Chemical composition*                              |
|-------------------|--------------------|--------------|-------------|---------------------------------------------------|
| Beautifil II      | Shofu, Kyoto, Japan| BE           | A2, A4, B3, C3 | bisphenol-A-diglycidyl methacrylate\(\geq7.5\%\)   |
|                   |                    |              |             | triethyleneglycol dimethacrylate\(<5\%\)          |
|                   |                    |              |             | aluminofluoro-borosilicate glass\(\geq70\%)        |
|                   |                    |              |             | \(\text{Al}_2\text{O}_3\)                         |
|                   |                    |              |             | camphorquinone                                    |
| Clearfil Majesty  | Kuraray Noritake Dental, Tokyo, Japan | CM       | A2, A4, B4, C4 | bisphenol-A-diglycidyl methacrylate 2.5–10\%       |
| ES-2              |                    |              |             | silanated barium glass filler                      |
|                   |                    |              |             | pre-polymerized organic filler                     |
|                   |                    |              |             | hydrophobic aromatic dimethacrylate                |
|                   |                    |              |             | hydrophobic aliphatic dimethacrylate               |
|                   |                    |              |             | camphorquinone, accelerators, initiators, pigments |
| Estelite Σ Quick  | Tokuyama Dental, Tokyo, Japan | EL       | A2, A4, B4, C3 | bisphenol A di(2-hydroxy propoxy)                  |
|                   |                    |              |             | dimethacrylate 10–30\%                            |
|                   |                    |              |             | triethylene glycol dimethacrylate 5–10\%          |
|                   |                    |              |             | camphorquinone<1\%                                 |
|                   |                    |              |             | dibutyl hydroxy toluene<1\%                        |
|                   |                    |              |             | mequinol<1\%                                       |
|                   |                    |              |             | 0.2-μm monodispersing spherical filler (Si-Zr)     |
| Solare            | GC, Tokyo, Japan   | SO           | A2, A4, B3, C3 | urethane dimethacrylate 15–30\%                   |
|                   |                    |              |             | fluoro alumino-silicate glass 30–40\%             |
|                   |                    |              |             | silica powder 10–20\%                              |
|                   |                    |              |             | prepolymized filler 20–30\%                        |
|                   |                    |              |             | dimethacrylate 0–5\%                               |
|                   |                    |              |             | Camphorquinone                                     |
| Venus             | Kulzer, Hanau, Germany | VN        | A2, A4, B3, C4 | bisphenol-A-diglycidyl methacrylate                |
|                   |                    |              |             | triethyleneglycol dimethacrylate                    |
|                   |                    |              |             | \(\text{SiO}_2\) and barium glass 78 wt%           |
|                   |                    |              |             | photoinitiator                                      |

*described by the manufacturers’ SDS and technical report*

and \(b^*\) describe the chromaticity on the green-red and blue-yellow chromatic coordinates, respectively. In the spectrophotometer, \(D_65\) illumination light with 8° diffusion geometry from a pulsed xenon lamp was used to irradiate specimens, which were centered in a \(\phi 3.0\)-mm aperture. The light reflected from the specimen was corrected with the \(\phi 40\)-mm integrating sphere and detected with a 32-element photo-conductive line sensor to resolve the light with a wavelength pitch \(<10\) nm. To exclude any specular reflected light, the specular component exclusion (SCE) mode at the back of a black box (CM-A182, Konica Minolta) was used for zero calibration was selected for the measurement (Fig. 1). During testing, the spectrometer was calibrated using a white reflectance standard (CM-A117, Konica Minolta) and the zero calibration black box at each operating temperature.

Materials were packed into a stainless-steel mold with a cylindrical hole (\(\phi 12\times1.0\) mm) on a glass plate which was covered by a second glass plate, and finger pressure was exerted to extrude excess material. The specimens were placed in a laboratory light-curing unit containing a 300 W xenon flash lamp (Heraflash, Heraeus Holding, Hanau, Germany), irradiated twice, from above and below, for 90 s, and then removed from the mold. The light intensity irradiated from the unit was 378 mW/cm² at 60 mm from the lamp, and which gave similar performance to the clinical light-curing
Fig. 1 Spectrophotometer for measurement of CIE $L^*a^*b^*$ color values in the chamber of a cool/hot incubator.
(a): specimen (which is completely covered with a black box during the test); (b): black box; (c): spectrophotometer; (d): white reflectance standard.

units. In order to irradiate uniformly to a large size specimen, the laboratory light-curing unit was used.

The specimens were warmed or cooled in a cool/hot incubator (EHC, temperature dispersion accuracy: ±1.5°C, As One, Osaka, Japan) at 4, 23, 37, 60, or 80°C for 300 min until prepared for measurements.

The spectrophotometer was operated in a cool/hot incubator (A5501, temperature dispersion accuracy: ±1.5°C, As One), and measurements were performed at operating temperature of 5°C for a specimen temperature of 4°C, 23°C for 23°C, and 35°C for 37, 60, and 80°C because the operating temperature of the instrument was restricted to 5–35°C.

Based on the color values, the color difference ($\Delta E^*$) among different specimen temperatures was calculated using the equation:

$$\Delta E^* = \sqrt{\Delta L^*^2 + \Delta a^*^2 + \Delta b^*^2}$$

where, $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ are the changes in specimen temperatures.

Optical refractive index

The optical refractive index of the material was measured using a high-precision Abbe refractometer (NAR-3T, Atago, Tokyo, Japan). The instrument is designed for measurement at a wide temperature range with high accuracy (refractive index at 589 nm wavelength ($n_0$): ±0.0002). The contact liquid monobromonaphthalene ($n_0=1.65$, RE-1190, Atago) was used to adhere the specimen to the refracting prism surface of the refractometer. Monochromatic light of 589 nm wavelength (D-line) from a LED lamp was used as the light source. The light passed through the longitudinal axis of the rectangular specimen. A detector placed on the back side of the refracting prism would show a light and a dark region for the reading. Measurements were performed at specimen temperatures of 4, 23, 37, 60, and 80°C. The instrument adjusted the scale by measuring the test piece ($n_0=1.5618$, RE-1197, Atago) at each operating temperature.

The A4 shade of all composite resins were selected for measurement. Commonly, for the Abbe refractometer, it is difficult to measure a translucent material such as a composite resin due to high light scattering within it, as the refractometer depends on the observer’s eye to determine the reading. The A4 shade was used because it had less light scattering and higher light transmittance than do other shades.

Materials were packed into a stainless steel rectangular mold (20×10×6 mm) on a glass plate. The specimens were placed in the laboratory light-curing unit and then irradiated from above and below for 120 s each. After polymerization, the rectangular specimens were removed from the mold and polished with #1200 SiC waterproof paper and a 0.05-μm alumina polishing suspension.

The specimens were warmed or cooled, and the color measurements were taken at each temperature. Using a water circulator (UCT-1000 and TR-1A, temperature accuracy: ±1.5°C, As One), water was passed through the instrument during measurements at an operating temperature of 5°C for specimens at 4°C, 23°C for 23°C, 37°C for 37°C, and 50°C for 60 and 80°C, because the operating temperature of the instrument was restricted to 5–50°C.

Statistical analysis

The mean values of the measured $L^*$, $a^*$ and $b^*$ values at 23, 37, 60, and 80°C were multiply compared with those at 4°C using Tukey’s test, respectively ($p<0.05$). The color difference and refractive index were analyzed using two-way analysis of variance (ANOVA, $\alpha=0.05$) to examine the effects of specimen temperatures and materials. One-way analysis of variance ($\alpha=0.05$) was also used to analyze the effect of materials on the color difference between 23 and 37°C. Due to significant differences between groups, multiple comparisons were made using Tukey’s test. Three specimens of each material were used for each measurement.

RESULTS

Color measurement

The CIE $L^*a^*b^*$ color values at specimen temperatures of 4, 23, 37, 60, and 80°C for all materials are shown in Tables 2 and 3. At the typical intraoral temperature of 37°C, the values for $L^*$ ranged from 47.34 for CM-C4 to 60.22 for VN-A2, those of $a^*$ ranged from −3.16 for EL-B4 to 2.92 for BE-A4, and those of $b^*$ ranged from 4.81 for BE-A2 to 17.84 for EL-A4. $L^*$ trended to decrease with increasing temperature from 4 to 80°C, and $a^*$ and $b^*$
There were significant differences in increased with increasing temperature for all materials. There were significant differences in $L^*$ values for all materials except with EL-B4, -C3, SO-A2 and VN-C4, and in $a^*$ values for all materials except with BE-C3, and in $b^*$ values for all materials except with BE-A4, -C3 and EL-B4 between 4 and 80°C ($p<0.05$).

Figure 2 shows the values of color differences ($\Delta E^*$) at 23, 37, 60, and 80°C compared with those at 4°C for

| Material | $L^*$ | $a^*$ | $b^*$ | $L^*$ | $a^*$ | $b^*$ | $L^*$ | $a^*$ | $b^*$ |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| BE-A2    | 61.20 (0.16) | -0.12 (0.05) | 4.89 (0.04) | 60.61 (0.16)* | -0.08 (0.06)* | 4.90 (0.06) | 60.02 (0.18)* | -0.08 (0.07)* | 4.81 (0.04)* |
| BE-A4    | 51.78 (0.26) | 2.79 (0.09) | 15.69 (0.29) | 51.21 (0.41)* | 2.88 (0.08)* | 15.63 (0.36) | 50.57 (0.31)* | 2.92 (0.08) | 15.62 (0.14) |
| BE-B3    | 58.23 (0.89) | -0.40 (0.12) | 9.49 (0.58) | 57.93 (0.26)* | -0.52 (0.09)* | 9.70 (0.46) | 57.09 (0.46)* | -0.19 (0.07)* | 9.65 (0.61) |
| BE-C3    | 52.86 (0.33) | 0.88 (0.07) | 9.34 (0.45) | 51.86 (0.28)* | 0.92 (0.08)* | 9.35 (0.47) | 51.24 (0.25)* | 0.98 (0.08) | 9.40 (0.42) |
| CM-A2    | 60.43 (0.04) | -2.10 (0.11) | 4.65 (0.12) | 60.00 (0.10)* | -2.13 (0.09)* | 4.91 (0.15)* | 59.73 (0.07)* | -2.11 (0.10) | 5.32 (0.07)* |
| CM-A4    | 50.92 (1.00) | 0.26 (0.35) | 13.77 (0.84) | 50.29 (0.94)* | 0.41 (0.30)* | 13.88 (0.59) | 49.90 (1.00)* | 0.64 (0.35)* | 14.43 (0.80)* |
| CM-B4    | 54.37 (0.71) | -2.22 (0.45) | 10.84 (0.90) | 53.70 (0.54)* | -1.89 (0.41)* | 11.49 (0.84)* | 53.31 (0.60)* | -1.57 (0.46)* | 12.03 (0.97)* |
| CM-C4    | 48.24 (0.26) | -0.30 (0.02) | 8.34 (0.15) | 47.56 (0.38)* | 0.01 (0.02)* | 8.92 (0.13)* | 47.34 (0.40)* | 0.28 (0.02)* | 9.37 (0.07)* |
| EL-A2    | 56.68 (0.40) | -2.03 (0.08) | 10.35 (0.38) | 56.42 (0.47)* | -2.18 (0.08)* | 10.18 (0.42)* | 56.29 (0.38)* | -2.30 (0.07) | 10.05 (0.37)* |
| EL-A4    | 51.10 (0.12) | 0.44 (0.07) | 18.57 (0.14) | 50.80 (0.07)* | 0.33 (0.08)* | 18.20 (0.15)* | 50.70 (0.13)* | 0.22 (0.06) | 17.84 (0.05)* |
| EL-B4    | 53.84 (0.22) | -3.13 (0.08) | 16.60 (0.50) | 53.67 (0.24) | -3.11 (0.10) | 16.54 (0.47) | 53.61 (0.20)* | -3.16 (0.08) | 16.52 (0.45)* |
| EL-C3    | 49.89 (0.56) | -1.06 (0.19) | 14.14 (0.25) | 49.84 (0.57)* | -1.06 (0.19) | 14.09 (0.32) | 49.68 (0.53)* | -1.10 (0.19)* | 14.06 (0.31)* |
| SO-A2    | 58.45 (0.16) | -1.24 (0.04) | 5.20 (0.20) | 58.23 (0.42) | -1.12 (0.06)* | 5.90 (0.22)* | 58.09 (0.35) | -1.14 (0.06)* | 6.13 (0.22)* |
| SO-A4    | 54.68 (0.31) | -0.25 (0.12) | 12.69 (0.22) | 54.32 (0.32)* | -0.15 (0.11)* | 12.91 (0.23)* | 54.05 (0.31)* | -0.01 (0.11)* | 13.22 (0.25)* |
| SO-B3    | 59.55 (0.76) | -2.31 (0.18) | 9.44 (0.56) | 59.28 (0.91) | -2.20 (0.13)* | 9.77 (0.36) | 59.05 (0.97)* | -2.06 (0.14)* | 10.28 (0.34)* |
| SO-C3    | 57.02 (0.08) | -0.95 (0.05) | 7.32 (0.02) | 56.85 (0.23) | -0.89 (0.06)* | 7.68 (0.13)* | 56.69 (0.12) | -0.81 (0.05)* | 8.21 (0.07)* |
| VN-A2    | 60.83 (0.48) | -1.84 (0.17) | 3.68 (0.61) | 60.36 (0.75) | -1.77 (0.16)* | 4.41 (0.62)* | 60.22 (0.62)* | -1.72 (0.14)* | 4.87 (0.54)* |
| VN-A4    | 55.15 (0.17) | -0.88 (0.03) | 11.67 (0.04) | 54.72 (0.18)* | 0.70 (0.04)* | 12.47 (0.12) | 54.53 (0.14)* | -0.49 (0.04)* | 13.13 (0.07)* |
| VN-B3    | 58.68 (0.07) | -1.67 (0.12) | 11.11 (0.24) | 58.39 (0.16)* | -1.52 (0.10)* | 11.63 (0.19)* | 58.12 (0.15)* | -1.34 (0.10)* | 12.32 (0.19)* |
| VN-C4    | 52.42 (0.13) | -1.40 (0.06) | 8.06 (0.17) | 52.06 (0.19) | -1.21 (0.01)* | 8.77 (0.11)* | 51.75 (0.26)* | -1.04 (0.04)* | 9.53 (0.16)* |

Numbers in parentheses are standard deviations.
Symbols •, ■ and + show significant differences in $L^*$, $a^*$ and $b^*$ at 23, 37, 60, and 80°C compared with those at 4°C, respectively ($p<0.05$).
all materials. The values of $\Delta E^*$ between 4 and 60°C ranged from 0.31 for EL-C3 to 2.22 for VN-A4, and those between 4 and 80°C ranged from 0.38 to 3.87. For most materials, the color differences significantly increased with increasing temperature differences between 4°C and other temperatures. Two-way ANOVA showed that the color differences were significantly affected by specimen temperatures ($F=136.0$, $p<0.05$) and materials ($F=73.9$, $p<0.05$) and these interaction ($F=7.1$, $p<0.05$). EL-A2, -B4 and -C3 showed significantly lower color differences at 4/37, 4/60 and 4/80°C than other materials ($p<0.05$), and EL-A2 and -B4 showed no significant difference among color difference at all specimen temperatures ($p>0.05$).

The values of $\Delta E^*$ between 23 and 37°C for all materials are shown in Fig. 3. The values of $\Delta E^*$ ranged from 0.16 for EL-B4 to 1.05 for BE-B3. ANOVA showed that the color differences were significantly affected by materials ($F=7.9$, $p<0.05$). BE-B3 and EL-C3 showed significantly higher and lower color differences than other materials, respectively ($p<0.05$).

### Optical refractive index

The variations in optical refractive index for all A4 shade of materials at 4, 23, 37, 60, and 80°C are shown in Fig. 4. The refractive indices at 37°C were 1.537 for BE-A4, 1.548 for CM-A4, 1.539 for EL-A4, 1.505 for SO-A4, and 1.532 for VN-A4. For all materials, the values ranged from 1.512 to 1.555 at 4°C and decreased consistently, with minimum values of 1.501–1.544 at 80°C. Two-way ANOVA showed that the refractive indices were significantly affected by specimen temperatures ($F=53.2$, $p<0.05$) and materials ($F=1077.0$, $p<0.05$). The refractive indices gradually decreased with increasing specimen temperature. There were significant differences in refractive indices between 4 and 80°C for all materials ($p<0.05$).
DISCUSSION

The CIE $L^*$, $a^*$, and $b^*$ color values significantly changed with variations in the specimen temperature for most of the materials used in this study (Tables 2 and 3). The $\Delta E^*$ values, which were obtained from $L^*$, $a^*$, and $b^*$ color values, ranged from 0.31 to 3.22 units between 4 and 60°C at intraoral temperatures (Fig. 2). Several studies have reported that color differences in dental restorative materials ranging from 2.0 to 3.0 units are perceptible. About half of the materials studied had color differences larger than 2.0 units, and VN-A4 had value larger than 3.0 units between 4 and 60°C. The maximum color difference between 4 and 80°C was 3.87 units. This result indicates that temperature had a considerable impact on color change in the composite resins, with perceptible thermochromism even between 4 and 60°C at intraoral temperatures. Moreover, between 23 and 37°C, most of the materials showed color differences larger than 0.4 units, which can be detected by a trained eye (Fig. 3). Thermochromism in restorative composite resin occurs with a small temperature change, between regular room temperature of 23°C and a normal intraoral temperature of 37°C, although the color change may be not large enough to be easily detected.

In general, any substance can demonstrate
thermochromic effect is complex\textsuperscript{9,10}, but basically, it is caused by changes in optical properties, such as light transmittance, reflectance, absorbance, or scattering, and it can also be induced by a change in temperature\textsuperscript{1,12}. Several factors have been reported to influence the definitive color of restorative composite resins, such as pigments, photo initiators, and incorporated fillers\textsuperscript{13–15}. The EL, which incorporated the supra-nano monodispersing spherical filler\textsuperscript{16}, showed lower thermochromic effect than other materials, especially CM and VN. CM and VN incorporated irregular and different particle diameters fillers\textsuperscript{16}. The shape of filler particle, as well as particle size, may play an important role for the thermochromism of composite resins\textsuperscript{15}. However, full understanding of the relationship between temperature and the optical properties of composite resins is fundamental to assessing the thermochromism of composite resins.

The refractive index, which is the most important optical constant among several optical properties, of A4 shade of materials at 37ºC ranges from 1.505 to 1.548 (Fig. 4). No previous study has reported the refractive index of restorative composite resins at the typical intraoral temperature of 37ºC, and its temperature dependence. The values we obtained are close near to the refractive indices of the base resins, which were isolated from three commercial composite resins, and ranged from 1.51 to 1.55, as reported in a previous study\textsuperscript{17}, although refractive indices of the base resins, which were isolated from three commercial composite resins, and ranged from 1.51 to 1.55, as reported in a previous study\textsuperscript{17}, although temperature data during measurements in that study were not reported. The refractive indices for all materials significantly decreased with increasing temperature from 4 to 80ºC. The changes in refractive indices for all materials ranged from −0.51 to −0.71% for an increase from 4 to 80ºC. The decreasing ratios obtained were also near the −0.18% reported for industrial-use polymethyl methacrylate resin for an increase from 20 to 40ºC\textsuperscript{18}, and about −0.60% of polycarbonate resin for an increase from 15 to 75ºC\textsuperscript{19}. The thermal dependence of SiO\textsubscript{2} glass, which is used as filler particles in the composite resin, is extremely small in comparison with the base resin, for example, the linear-thermal expansion coefficient of SiO\textsubscript{2} glass is only about one two-hundreth of the Bis-GMA and Tri-EDMA comonomers\textsuperscript{20,21}. Therefore, it can be presumed that the refractive index and temperature dependence of a composite resin are controlled by those of the base resin, which is main structure of a composite resin. On the other hand, a previous study\textsuperscript{22} reported that the linear-thermal expansion coefficient of the four commercial composite resins ranged from $17.0 \times 10^{-6} \text{ºC}^{-1}$ to $39.0 \times 10^{-6} \text{ºC}^{-1}$. This means that the cubic-thermal expansion ranged from 0.39 to 0.89% at 4–80ºC. Thermal expansion would decrease the density of the material. Both values are inversely related to the change in temperature. In general, the refractive index of a transparent material decreases linearly with its density\textsuperscript{23}. It is thought that the thermal expansion of composite resins decreases their density, thereby decreasing the refractive index.

The refractive index determines light reflection and transmittance of a material when incident light enters it. In the case of normal incident light (i.e., incident angle $\theta=0$) reaching the material from air, the light reflectance ($R$) at the surface of the material is calculated according to the following Fresnel’s equation, which describes the behavior of incident and reflected light when moving between media with different refractive indices:

$$R=\left(\frac{n_1-n_2}{n_1+n_2}\right)^2 \times 100(\%) \quad (2)$$

where, $n_1$ and $n_2$ are refractive indices of air ($n_1 \approx 1.0$) and the composite resin, respectively.

In the case of CM-A4, which had the highest refractive index among the tested materials, the refractive index measured was 1.555 at 4ºC and 1.544 at 80ºC, so the calculated values of light reflectance were 4.71 and 4.58% at each temperature, respectively. Therefore, the temperature rise from 4 to 80ºC would cause a reduction in the light reflectance of 2.86% for normal incident light. This tendency was also seen for other materials as reductions in the light reflectance ranged from 2.29 to 3.34%. On the other hand, for all materials, the values of the $L^*$ parameter, which is the brightness coordinate, decreased with a rise in

| Material | $L^*$ Change | $a^*$ Change | $b^*$ Change |
|----------|--------------|--------------|--------------|
| BE-A2    | −2.33        | 0.24         | 0.45         |
| BE-A4    | −2.47        | 0.44         | 0.03         |
| BE-B3    | −1.61        | 0.17         | 0.52         |
| BE-C3    | −2.32        | 0.00         | 0.05         |
| CM-A2    | −0.98        | 0.07         | 1.76         |
| CM-A4    | −1.72        | 1.07         | 1.84         |
| CM-B4    | −1.32        | 1.19         | 2.33         |
| CM-C4    | −1.38        | 1.26         | 2.58         |
| EL-A2    | −0.30        | −0.50        | −0.21        |
| EL-A4    | −0.24        | −0.45        | −1.46        |
| EL-B4    | −0.04        | −0.18        | −0.62        |
| EL-C3    | −0.01        | −0.13        | −0.34        |
| SO-A2    | −0.56        | 0.20         | 2.17         |
| SO-A4    | −0.79        | 0.71         | 1.85         |
| SO-B3    | −0.86        | 0.55         | 2.34         |
| SO-C3    | −0.82        | 0.29         | 2.12         |
| VN-A2    | −0.75        | 0.29         | 3.38         |
| VN-A4    | −0.55        | 0.90         | 3.72         |
| VN-B3    | −0.45        | 0.67         | 3.22         |
| VN-C4    | −0.27        | 0.57         | 3.57         |
temperatures would cause a reduction in the $L^*$ value of the composite resins, i.e., it would appear darker. The changes in $L^*$ value would considerably affect the color difference ($\Delta E^*$) obtained from equation (1) as well as $a^*$ and $b^*$ values. Although the thermochromic effect cannot be determined only by one optical property, these facts indicate that the change in refractive index and light reflectance induced by a change in temperature could be one of the explanations for the thermochromism of the composite resins. In contrast, the $a^*$ and $b^*$ parameters, which are chromatic coordinates, also varied with temperature. The color chromaticity of the composite resin is predominantly controlled by a different type and content of pigments incorporated into it\(^7\). However, no theoretical or experimental research for the thermochromic effect of pigments used in the composite resins is known, more investigation concerning the detailed mechanism of thermochromism of the composite resins caused by pigments will be needed in a further study.

Clinically, it should be pointed out that restorative composite resins show perceptible thermochromism at typical intraoral temperatures, which can affect the aesthetics of restorations, although intraoral temperature changes spanning from 4 to 60°C would not occur for a long time.

Furthermore, for any laboratory colorimetric measurements of dental restorative materials, it is strongly recommended that the temperature of materials, measuring instruments, and laboratory conditions be carefully monitored.

CONCLUSIONS

1. According to our results, the studied restorative composite resins exhibited perceptible color changes at intraoral temperatures, i.e., thermochromism of the composite resin.

2. At a typical intraoral temperature of 37°C, the refractive index for the A4 shade composite resins ranged from 1.505 to 1.548. The values consistently decreased with increasing temperature for temperatures from 4 to 80°C.

3. Optical properties that change in response to temperature variations, such as refractive index and light reflectance, could affect the thermochromism of composite resins.

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