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Most manufacturers do not provide details about the photoinitiators contained in dental adhesives. Therefore, it is difficult to choose an optimal combination of dental adhesive and light-curing unit. The purpose of this study was therefore to investigate the spectral emission characteristics of several commercially available light-curing units and the spectral transmittance characteristics of contemporary dental adhesives. Spectral distributions of emitted lights were determined on a UV-vis-NIR spectrometer for three quartz-tungsten-halogens (QTH) light-curing units (Jetlite 3000, J. Morita; New Light VL-2, GC; D-Lux 2000, Dentrade) and three light-emitting diode (LED) light-curing units (Curenos, Shofu; G-Light Prima, GC; Bluephase, Ivoclar Vivadent). Spectral distributions of light transmittance in contemporary dental adhesives (Scotchbond Multi-Purpose, 3M ESPE; Adper Single Bond, 3M ESPE; One-Step, Bisco; AQ Bond Plus, Sun Medical; Optibond All-in-One, Kerr; Clearfil S Bond, Kuraray Medical; G-Bond, GC; Tokuyama Bond Force, Tokuyama Dental; GBA 300 experimental, GC) were also determined. Each of the three QTH light-curing units had a wide emission range of 380-510 nm. A narrower emission range was observed in the LED light-curing units than in the QTH light-curing units. It was found that 2 LED light-curing units had dual peak wavelengths in both the blue and violet regions of the visible spectrum. There were some variations in light transmittance, and therefore the results suggested that some dental adhesives contain alternative photoinitiators besides camphorquinone. The selection of suitable light-curing units on the basis of the light absorption of dental adhesives and resin composites in dental clinics is of utmost importance.

Keywords: light-curing unit, dental adhesive, photoinitiator, light-emitting diode, absorption spectra, emission spectra

1. Introduction
Recently a new type of light-curing unit has been developed that uses blue-light emitting diodes (blue-LEDs) [1, 2]. The LED light-curing unit exhibits better performance than conventional quartz-tungsten-halogens (QTH) light-curing units due to its portability (it is cordless and small in size), lower power consumption, longer life span and lower heat generation [3]. Therefore, the market share of LED light-curing units is rapidly growing [4].

The types of resin composite restorative materials that are in demand have recently changed. To meet the aesthetic needs of clients,
bleaching-white composites have been developed to match very light shades. Some of these composites include alternative photo initiators such as 1-phenyl-1,2-propanedione (PPD) [5], 2,4,6-trimethylbenzoyl diphenylphosphine oxide (MAPO or Lucirin TPO) [6], and bis (2,4,6-trimethylbenzoyl)-phenylphosphine oxide (BAPO or Irgacure 819) [7], in order to avoid residual yellowing caused by camphorquinone (CQ) [8-10].

The types of resin-tooth adhesive systems that are in demand have also changed. One-step self-etch adhesives (1-SEAs) are becoming increasingly popular. Since these simplified adhesives are blended with a hydrophilic component(s) and a high concentration of solvent in hydrophobic dimethacrylates, the steps of etching, priming, and bonding can be performed simultaneously [11]. Therefore, use of these adhesives is less time consuming, and reduces the number of complicated application steps. On the other hand, it has been reported that, with respect to both enamel and dentin, these adhesives have lower bonding effectiveness and long-term bond durability than multi-step adhesives [11, 12]. One of the reasons for this has been commonly associated with their lower degree of polymerization caused by the presence of water [13]. Additionally, it is well known that the polymerization efficiency of the traditional photoinitiator CQ is considerably lower than that of alternative initiators [14-16]. Some products therefore include alternative initiators [17]. The absorption spectra of alternative initiators are distributed in the ultraviolet to violet regions and are different from those of CQ [14, 18, 19]. The use of these alternative initiators is therefore incompatible with the narrow spectrum of blue LED light-curing units. In order to overcome this problem, several manufacturers have developed dual- or multi-wavelength LED light-curing units. Unfortunately, most manufacturers do not provide details regarding the photoinitiators contained in commercially available dental adhesives. Therefore, it is difficult to choose an optimal combination of dental adhesive and light-curing unit. The purpose of this study was, therefore, to analyze the spectral emission characteristics of several commercially available light-curing units and the spectral transmittance characteristics of contemporary dental adhesives by using an ultraviolet-visible light-near infrared (UV-vis-NIR) spectrophotometer.

2. Materials and Methods

2.1. Spectral analyses of light-curing units

The setup for the spectral analysis of each light-curing unit is schematically shown in Fig. 1. Six light-curing units were evaluated for spectral analysis (Table 1). The light was directed through an optical fiber (Ocean Optics, Dunedin, FL, USA) connected to a UV-vis-NIR spectrophotometer (USB-4000, Ocean Optics), and emission spectra were determined at 0.2 nm intervals. The obtained data were recorded and analyzed on a computer connected to the spectrophotometer. Each emission spectrum was determined in three different irradiation modes in G-Light Prima.

![Fig. 1. Schematic illustration of the spectral measurement of light-curing unit](image)

Table 1. Light-curing units used in this study

<table>
<thead>
<tr>
<th>Light-curing unit (Manufacturer)</th>
<th>Mode</th>
<th>Power density (mW/cm²)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Lux 2000 (Dentrade, Osaka, Japan)</td>
<td>-</td>
<td>1250</td>
<td>8</td>
</tr>
<tr>
<td>New Light VL-2 (GC, Tokyo, Japan)</td>
<td>-</td>
<td>700</td>
<td>11</td>
</tr>
<tr>
<td>Jetlite 3000 (J. Morita USA, CA, USA)</td>
<td>-</td>
<td>790</td>
<td>11</td>
</tr>
<tr>
<td>Curenos (Shofu, Kyoto, Japan)</td>
<td>-</td>
<td>1550</td>
<td>8</td>
</tr>
<tr>
<td>G-Light Prima (GC, Tokyo, Japan)</td>
<td>Normal</td>
<td>1150</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>52</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>PH</td>
<td>1150</td>
<td>8</td>
</tr>
<tr>
<td>Bluephase (Ivoclar Vivadent, Schaan, Lichtenstein)</td>
<td>High</td>
<td>1120</td>
<td>9</td>
</tr>
</tbody>
</table>
2.2. Spectral analyses of light transmittance through dental adhesives

The procedure for the spectral analyses of light transmittance is schematically shown in Fig. 2. Eight commercially available dental adhesives and one experimental dental adhesive were investigated for analyses of light transmittance (Table 2). A deuterium tungsten halogen light source (DH-2000, Ocean Optics, Dunedin, FL, USA) was connected to a UV-vis-NIR spectrophotometer (USB4000) using two optical fibers separated by a sample holder. One drop of the unfilled resin was placed onto a thin glass plate (thickness: 0.15 mm; Matsunami Glass Industries, Ltd., Kishiwada, Osaka, Japan), covered with another glass plate, and gently compressed using finger pressure. Immediately afterwards, each resin sample was placed in the sample holder and irradiated with light. The light transmission spectra through each adhesive sample were acquired in 0.2 nm increments.

3. Results

3.1. Emission spectra of light-curing units

The emission spectra of the light-curing units are shown in Fig. 3. Each of the three QTH light-curing units had a wide emission range of 380-510 nm. The peak wavelength of D-Lux 2000 (473.4 nm) was slightly shorter than New-Light VL-2 and Jetlite 3000 (491.0 nm). The Curenos LED light-curing unit had a narrower emission range than that of QTH light-curing units; a range of 420-510 nm with a peak in the blue region (462.9 nm). Both the normal mode and PH mode of G-Light Prima had an emission peak wavelength at 462.9 nm, which was the same as that of Curenos. However, these modes had one more peak in the violet region (402.9 nm). The peak height ratios (blue/violet) in the normal mode and PH mode were 1:0.0956 and 1:0.6265, respectively. Bluephase G2 had also two emission peaks in the blue and violet regions of the visible spectrum (410.3 nm and 454.6 nm). The peak height in the blue region was slightly lower than that in the violet region (blue/violet = 0.9455:1). G-Light Prima PL mode had only one emission peak in the violet region (402.9 nm).

3.2. Spectral characteristics of light transmittance of dental adhesives

Spectra of light transmittance in each adhesive are shown in Fig. 4. Similar spectral characteristics were found in the light transmittance of Scotchbond Multi Purpose, Adper Single Bond, One-Step, OptiBond All-in-One, and Tokuyama Bond Force. Although AQ Bond Plus also had similar characteristics, the transmittance in the range of 320-350 nm was slightly lower than that of the other adhesives (arrow head). Typically shaped inverted peaks were found in the range of 355-410 nm for Clearfil S³ Bond, G-Bond and GBA 300 (pointer).
Discussion

A conventional QTH lamp emits white light with a wide emission range between UV and NIR. In order to apply this light source in the polymerization of light-cured dental materials, unwanted wavelengths must be eliminated by placing filters between the light source and light guide so as to prevent harmful effects and pulpal damage by heat generation [20]. In this study, peak wavelength and emission range slightly differed among the three QTH light-curing units. This may be due to the different filters used. However, all these light-curing units reacted well to CQ, because the emission range and peak wavelengths of these light-curing units were almost the same as the reaction range and reaction peak wavelength of CQ.

The emission range of Curenos was the same as that of a typical LED light-curing unit, and this finding was similar to that of a previous report [20]. On the other hand, G-Light Prima and Bluephase G2 employ two different LED series in the same device allowing them to operate in both blue and violet regions of the spectrum, and these devices are categorized as third-generation LED light-curing units [9, 20]. In our data, two peaks could also be found in both the violet and blue regions. However, the peak height ratios were different: G-Light Prima mainly used the blue LEDs and supplementarily used the violet LED(s) in both normal mode and PH mode. In Bluephase G2, on the other hand, blue LEDs and violet LEDs were equally used. Furthermore, the peak wavelength of its blue LED was slightly shorter than that of G-Light Prima. These differences might have an effect on curing behavior, even if the power density level is the same.

In some previous studies, the absorption spectra of photoinitiators have been investigated by spectrophotometry [9, 14, 19]. However, in these previous studies, it is possible that the light absorption was not measured directly, and reflection, refraction, and scattering may have been
included in the measurement. Therefore, in the present study, the spectral characteristics for light transmittance through dental adhesive were determined.

A dip in the spectra was observed in the range of 430-490 nm, with an inverse peak ($\lambda_{\text{max}}$) at around 470 nm in all adhesives tested. This may indicate that these adhesives include CQ. However, the reduction of transmittance was small. CQ is excited to an unstable triplet state that interacts with a tertiary amine to generate free radicals by absorption of blue light, and the polymerization of resin monomers caused by the breaking of carbon–carbon double bonds occurs [8]. On the other hand, it is well known that the polymerization efficiency of CQ is very low, because the maximum value of the molar extinction coefficient is significantly lower in CQ than other photoinitiators [14-16]. Recently, the micro-tensile bond strengths of experimental 1-SEAs containing different concentrations of CQ have been determined, and it has been concluded that minimally 0.7 wt % CQ should be used [21]. However, such a concentration might cause undesirable aesthetic effects [22].

Three inverse peaks were also found at 366 nm, 381 nm and 396 nm in Clearfil S3 Bond, G-Bond and GBA 300, respectively. The peak distribution was similar to that of Lucirin TPO [9, 14, 18, 19, 23]. It was therefore noted that Lucirin TPO might be included in these adhesives as a supplementary photoinitiator, which not only contributes to enhance the polymerization efficiency with a QTH light source but also reduces the yellowing of adhesives.

The first version of AQ Bond (Sun Medical) did not include CQ, but rather included an alternative initiator [24]. Since its absorption was distributed between the UV and violet regions, it could not be polymerized by a blue-LED light-curing unit [24]. Soon after, it was improved to AQ Bond Plus, which contained both CQ and the other photoinitiator [25]. In this study, the transmittance in the range of 330-350 nm was lower than that of the adhesives which contained only CQ, which might be due to the presence of the other photoinitiator. However, we could not identify the component of the photoinitiator.

5. Conclusions

In this study, the difference in the wavelength distribution of contemporary light-curing units was determined. Furthermore, we could clarify that some commercially available dental adhesives contained an alternative photoinitiator besides CQ. However, the influence of the light-curing unit and dental adhesive on polymerization efficiency, mechanical properties and residual yellowing has not yet been clarified. Further studies are therefore needed to investigate those points.

Acknowledgments

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