**Abstract**

**Aim** To compare changes in pulpal chamber temperature during the visible-light curing of direct pulp capping compounds and various modes of diode laser irradiation without prior placement of a pulp capping compound and the resultant seals.

**Materials and methods** Pulp exposure holes were made in 100 extracted human primary first molars, which were randomly assigned to ten equal groups. The holes were sealed by (a= Group 1, 2, 3, 4, 5, 6 and 7) different pulp capping compounds which were cured using various types of visible-light curing units or (b=Group 8, 9 and 10) diode laser irradiation without prior application of a pulp capping compound. Pulpal chamber temperatures were recorded during the procedure, and the resultant seals were examined under a scanning electron microscope.

**Results** Visible-light curing of the pulp capping compounds and diode laser irradiation at a 0.7 W output power can cause non-injurious temperature rises in the pulpal chamber. At higher output powers of the diode laser, the temperature rises are sufficient to cause thermal injury. The seals were complete when pulp capping compounds were used for direct pulp capping, but were incomplete when laser irradiation without prior placement of a pulp capping compound was used for the identical purpose.

**Conclusion** The visible-light curing of pulp capping compounds is not harmful to vital pulp, and provides an effective seal of the pulp exposure hole. Laser irradiation is not an effective sealant, and can cause thermal injury to vital pulp at high output powers.

**Keywords** Dental lasers; Dentine bonding agent; Direct pulp capping; Paediatric dentistry; Primary tooth pulp therapy; Visible-light curing device.

**Introduction**

Direct pulp capping is a procedure which is performed for maintaining the vitality of the pulp when vital pulp is exposed during cavity preparation or removal of carious dentine. The ideal compound for direct pulp capping should control infection, adhere to dentine in order to prevent microleakage, promote dentine bridge formation, and be clinically simple to handle [Tziafas et al., 2000]. Calcium hydroxide (CH)-based cements are widely used for direct pulp capping because of their ability to induce dentine bridge formation [Ford et al., 1996]. However, CH-based cements are poor sealants and are very soluble. Therefore, they cannot prevent microleakage, and usually dissolve within one or two years following their application [Baroudi et al., 2009]. Hence, the clinical outcome has often been disappointing, and this has prompted a search for alternative compounds for direct pulp capping.

One of the proposed solutions to overcome the disadvantages of CH-based cements and their poor clinical outcome is to incorporate visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010]. Dentine bonding agents are usually cured by light that is emitted by visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010]. Dentine bonding agents are usually cured by light that is emitted by visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010]. Dentine bonding agents are usually cured by light that is emitted by visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010]. Dentine bonding agents are usually cured by light that is emitted by visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010]. Dentine bonding agents are usually cured by light that is emitted by visible-light curing methacrylate-based resins into formulations of CH-based cements. The inclusion of these resins increases the binding of CH-based cements to dentine, as well as their resistance to acid dissolution and improves their handling characteristics [Cox et al., 1985]. Despite manufacturers’ instructions to the contrary, dentine bonding agents have also been used for direct pulp capping [Watts et al., 1994]. Hence, some direct pulp capping preparations also contain a reparative dentine bonding agent [Katoh et al., 2010].
modification of dentinal structures, and endodontic procedures, such as pulp vitality evaluation, dental pulp capping, pulpotomy, and root canal sterilisation [Coluzzi, 2004]. Some investigators have suggested that direct pulp capping could be done by laser irradiation before applying a pulpal dressing to the exposed pulp [Hasheminia et al., 2010; Moritz et al., 1988]. However, it has been reported that the increase in the pulpal chamber temperature when laser irradiation is used for direct pulp capping can cause pathologic changes in the pulpal tissue [Srimaneepong et al., 2002; Zach and Cohen, 1965].

It is against this background that we carried out a study that tested the hypotheses that (a) the rise in the pulpal chamber temperature is lower when LCUs are used to cure pulp capping compounds than that when diode laser irradiation without prior placement of a dental capping compound is used for the identical purpose, and (b) the sealing performances of pulp capping compounds and diode laser irradiation without prior placement of a dental capping compound.

Materials and methods

Specimen collection and preparation

The study comprised 100 freshly extracted human primary first molars, which were free of caries and developmental defects and not undergone any previous restorations, and whose root resorption was less than two-thirds of the root length. Any superficial debris on each tooth was removed by a scaler after the tooth's extraction. The roots of each tooth were removed by cutting each root approximately 1 mm below the bifurcation with a diamond saw, and the pulp residues in the pulpal chamber were then removed. A standardised 3 mm x 2 mm x 2 mm cavity was made on the mesio-occlusal and disto-occlusal surfaces of each tooth using a 1-mm fissure diamond bur with a high-speed hand piece with water spray cooling. This cavity was made so that the LCUs, which were used for curing the pulp capping compounds, could be easily positioned between the cusps of the molar tooth and to ensure that light from the LCU could be beamed at 90° at a constant distance (~3mm). A 1-mm pulp exposure hole was made in the base of one of the standardised cavities using a 1-mm fissure diamond bur. The output powers of the LCUs that were used in the study were measured by a Demetron® radiometer (Kerr, Romulus, MI, USA).

Measurement of pulpal chamber temperature

A K-type thermocouple probe was inserted into the pulpal chamber through the cut distal root canal, and positioned in such a manner that the tip of the thermocouple probe was placed against the dentine below the pulp exposure hole. After placement, the probe's placement was then fixed using a silicon-based impression material. The pulpal chamber was filled with distilled water, whose temperature was maintained at 24°C, using a 25G 10-mm-long needle. The sample tooth was mounted in the cover plate of a water bath, whose temperature was also maintained at 24°C (Fig. 1). For recording data, the thermocouple was connected to a data logger, and the pulpal chamber temperatures were captured at 2-second intervals.

Experimental groups

The 100 teeth were randomly divided into ten groups of ten teeth each. The ten experimental groups were named according to the different pulp capping compounds and the methods used for direct pulp capping and sealing the pulp exposure hole.

- Group 1 (control): the pulp exposure hole was sealed using Life®, a hard-setting CH-based cement (Life®, Kerr Italia S.p.a, Salerno, Italy), which was first mixed according to the manufacturer’s recommendation, and then placed in the pulp exposure hole using a 1-mm diameter ball-pointed instrument.

- Groups 2, 3 and 4: the pulp exposure hole was sealed with a visible-light curing CH-based cement (Calcimol LC®, Voco, Cuxhaven, Germany). For Group 2, the Calcimol LC® was cured by light that was emitted from a 650 mW/cm² QTH lamp (Hilux Optimax, Benlioglu, Ankara, Turkey) for 20 seconds. For Group 3, the Calcimol LC® was cured by light that was emitted from a 1000 mW/cm² VALO® LED (Ultradent, South Jordan, UT, USA) in the standard power mode for 20 seconds. For Group 4, the Calcimol LC® was cured by light that was emitted from a 4500 mW/cm² VALO® LED (Ultradent, South Jordan, UT, USA) in the extra power plasma mode for 3 seconds.

- Groups 5, 6 and 7: the pulp exposure hole was...
sealed using FuturaBond M®, a light-curing single-component dentine bonding agent (FuturaBond M®, Voco, Cuxhaven, Germany). The FuturaBond M® was first placed in the pulp exposure hole, and after waiting 20 seconds, it was then gently spread using pressurised air for five seconds. For Group 5, the FuturaBond M® was cured by light that was emitted from a 650 mW/cm² ATTEST ESPONENTE QTH lamp (Hilux Optimax®, Benlioglu, Ankara, Turkey) for 20 seconds. For Group 6, the FuturaBond M® was cured by light that was emitted from a 1000 mW/cm² VALO® LED (Ultradent, South Jordan, UT, USA) in the standard mode for 20 seconds. For Group 7, the FuturaBond M® was cured by light that was emitted from a 4500 mW/cm² VALO® LED (Ultradent, South Jordan, UT, USA) in the extra power plasma mode for 3 seconds. In order to check whether the pulp exposure hole had been sealed with the bonding agent, the hole was gently probed using a dental explorer.

Groups 8, 9 and 10: the pulp exposure hole was treated by two 10-second bursts of laser radiation using an 808-nm laser diode (Doctor Smile Dental Laser, Lambda Scientifica SpA, Altavilla Vicentina, Italy). No dental capping compound was placed in the pulp exposure hole before laser irradiation. The laser beam was delivered as a continuous wave, and the beam was manually directed perpendicular over the pulp exposure hole in a non-contact mode at a working distance of approximately 1 mm. The output power of the diode laser was (a) 0.7 W (recommended by the manufacturer) for Group 8, (b) 1 W for Group 9, and (c) 1.5 W for Group 10.

Scanning electron microscopy

After direct pulp capping, 5 teeth were randomly chosen from each treatment group in order to (a) evaluate the pulp exposure hole, (b) appraise the surface integrity of the pulp capping compound, and (c) make a qualitative morphological analysis of the seal between the pulp capping compound and the margin of the pulp exposure hole using a scanning electron microscope (SEM) (Jeol JSM 6400 SEM, Tokyo, Japan). For these purposes, the specimens were first sputter-coated with gold-palladium using a sputtering system (SEM Coating Unit E 500, Polaron Equipment Limited, Barcelona, Spain) before the examination.

Statistical analysis

The data were statistically analysed by one-way analysis of variance and the Duncan post-hoc test using a computerised statistical software program (SPSS 12.0 for Windows, Chicago, IL, USA). Data are presented as mean ± standard deviation, and the level of statistical significance was set at 5%.

Results

Changes in pulpal chamber temperature

Table 1 summarises the mean rises in pulpal chamber temperature after curing the various pulp capping compounds and sealing the pulp exposure holes by the different LCUs or the various modes of laser irradiation. All methods caused a rise in pulpal chamber temperature. When we compared the temperature rises that were induced by each method, we found

<table>
<thead>
<tr>
<th>GROUPS</th>
<th>N</th>
<th>MEAN TEMPERATURE RISE (°C) AND SEM EVALUATION</th>
</tr>
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<tbody>
<tr>
<td>Group 1</td>
<td>10</td>
<td>0.93±0.943* - (+) +</td>
</tr>
<tr>
<td>Group 2</td>
<td>10</td>
<td>0.76±0.541* + +</td>
</tr>
<tr>
<td>Group 3</td>
<td>10</td>
<td>1.64±1.032* + +</td>
</tr>
<tr>
<td>Group 4</td>
<td>10</td>
<td>1.96±1.463* + +</td>
</tr>
<tr>
<td>Group 5</td>
<td>10</td>
<td>1.60±1.341* + +</td>
</tr>
<tr>
<td>Group 6</td>
<td>10</td>
<td>1.98±1.247* + +</td>
</tr>
<tr>
<td>Group 7</td>
<td>10</td>
<td>2.31±1.248* + +</td>
</tr>
<tr>
<td>Group 8</td>
<td>10</td>
<td>1.73±1.121* + -</td>
</tr>
<tr>
<td>Group 9</td>
<td>10</td>
<td>6.32±3.21* + -</td>
</tr>
<tr>
<td>Group 10</td>
<td>10</td>
<td>13.2±4.217* + -</td>
</tr>
</tbody>
</table>

* Material surface cracks; +: undamaged/complete sealing; -: damaged/incomplete sealing.

The different direct pulp capping compounds and their curing methods and the three modes of diode laser irradiation are described in the Materials and Methods section. The values of the pulpal temperature rises that are followed by the same letter are not statistically significant from each other. Temperature data are expressed as mean ± standard deviation.

Statistical analysis

The data were statistically analysed by one-way analysis of variance and the Duncan post-hoc test using a computerised statistical software program (SPSS 12.0 for Windows, Chicago, IL, USA). Data are presented as mean ± standard deviation, and the level of statistical significance was set at 5%.

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that the highest temperature rise occurred in the pulpal chamber of Group 10, and the lowest temperature rise occurred in the pulpal chamber of Group 2. The rise in pulpal chamber temperature in Group 7 was almost 3 times higher than that found in Group 1 and Group 2. The temperature rise in the pulpal chamber of Group 9 was significantly smaller (p<0.05) than that recorded in the pulpal chamber of Group 10. In addition, the rises in pulpal chamber temperature of Groups 9 and 10 were significantly greater (p<0.05) than those recorded in the pulpal chamber of the other eight groups of treated teeth.

**SEM analysis of the seal after direct pulp capping**

Table 1 summarises the SEM findings on the surface integrity of the pulp capping compound after curing, and the integrity of the seal between the pulp capping compound and the dentine junction in the ten experimental groups. We observed that those pulp exposure holes that were not treated by laser irradiation, namely those of Group 1, 2, 3, 4, 5, 6, and 7, were completely sealed. Although diode laser irradiation at output powers of 0.7 W did not cause any cracks in and crazing of the margins of the pulp exposure holes (Figure 2A), laser irradiation at the higher output powers of 1 W and 1.5 W did cause cracks in and crazing of the margins of the pulp exposure holes (Fig. 2B). When Life® was used to seal the pulp exposure holes, we found that its surface was cracked and damaged (Fig. 2C). The seal between the pulp capping compound and the margins of the pulp exposure hole was complete when either Calcimol LC® (Fig. 2D) or FuturaBond M® was used to close the pulp exposure hole. This seal was incomplete when the hole was laser irradiated at all output powers.

**Discussion**

The degree and extent of tissue thermal injury depends on the temperature and duration of the exposure. Factors that influence the body’s ability to resist thermal injury include (a) the water content of the tissue, (b) the thickness of the tissue, (c) the presence or absence of insulating materials, and (d) the circulation within the tissue because the latter affects heat dissipation [Baldissara et al., 1997]. The dental pulp is temperature-sensitive, and a rise of 5.5°C in the pulpal chamber can cause damage to the dental pulp [Zach and Cohen, 1965]. In non-human primates, 15% of the dental pulp is irreversibly damaged when the intra-pulpal temperature is raised by 5°C, and 60% of the dental pulp is irreversibly damaged when the intra-pulpal temperature is raised by 12°C [Zach and Cohen, 1965]. Moreover, humans will experience pain without any long-term adverse consequences when the mean rise in intra-pulpal temperature of an intact tooth is 11°C (8.8°C – 14.7°C) and maintained for at least 1 minute [Baldissara et al., 1997]. Tjan and Dunn [1988] have also reported that the magnitude of the increase in intra-pulpal temperature is correlated with the thickness of the dentine because of dentine’s low heat conductivity. The increase in intra-pulpal temperature is low in teeth with a thick dentine layer. In addition, the pulp of an injured tooth is more heat-sensitive than that of an intact tooth. Our current knowledge on the effect of light curing of resin-based materials on intra-pulpal temperature when they are used for direct pulp capping is lacking. Hence, one of the aims of this study was to measure the magnitudes of the increases in pulpal chamber temperature that occur when various pulp capping compounds are cured by LCUs. A second aim of this study was to measure the increases in pulpal chamber temperature when diode laser irradiation is used for direct pulp capping before applying a pulpal dressing to the exposed pulp.

Pulp capping agents that contain a base and a catalyst are widely used for protection of dental pulp from injurious stimuli because some restorative treatments of teeth result in the rapid generation of thermal stimuli to
PULPAL CHAMBER TEMPERATURE AND SEALING PERFORMANCE OF VARIOUS DIRECT PULP CAPPING METHODS

the dental pulp [Schuurs et al., 2000]. The rise in pulpal chamber temperature that occurs during the curing of light-activated restorative materials has been attributed to their exothermic setting reactions and the energy that is absorbed during their light irradiation by LCUs [Lloyd et al., 1986; Shortall and Harrington, 1998]. We found that the visible-light curing of Life®, the control group for this investigation, caused the pulpal temperature to rise by 0.97°C. The probable reason for this small temperature rise might be due to exothermic setting reaction of this pulp capping agent. Shen [1996] reported that heat transfer through a material depends not only on the coefficient of thermal conductivity and the thermal diffusivity of the material, but also on its thickness. In addition, Saitoh et al. [2004] claimed that the thermal conductivity of visible-light curing CH-based cements depends on their organic matrix and inorganic filler content: the thermal conductivity of inorganic filler is 6-100 times higher than that of organic matrix. Fukase et al. [1992] claimed that cavity liners, such as visible-light curing CH-based cements, have thermal conductivity. It has also been claimed that the thermal conductivities of some constituents of some visible-light curing CH-based cements, namely eugenol, hydrocarbon resins, aromatic sulfonamides, and methyl salicylate polymers and monomers, are lower than those of their inorganic constituents or fillers, namely calcium hydroxide, calcium phosphate, zinc oxide, and barium sulfate. Calcimol LC®, one of the CH-based cements that we used in our study, contains hydrocarbon resins (40-48% UDMA and ≤ 2.5% 2-DMAEMA), and the inorganic fillers, CH and silicate. FuturaBond M®, the light-curing dentine bonding agent that we used in our study, also contains UDMA. When Calcimol LC® or FuturaBond M® is cured using different LCUs at different intensities and/or in different operating modes, the increases in pulpal chamber temperature were not significantly different from each other. This result differs from that of Little et al. [2005] who found that the thermal conductivity of CH-activated restorative materials was substantially higher than that of dentine bonding agents.

Utsunomiya [1988] reported that the formation of the dentine bridge occurred one week earlier after diode laser irradiation of exposed pulp surfaces in the dog’s teeth than in non-irradiated controls. In another study, Matsui et al. [2007] reported that the mineralisation of human pulp cells is stimulated by diode laser irradiation at output powers of 0.5 W or 1.0 W. Saltzman et al. [2005] investigated whether a diode laser pulpotomy, when used in conjunction with mineral trioxide aggregate (MTA), was an acceptable alternative for direct pulp capping to the conventional formocresol-zinc oxide eugenol pulpotomy. However, the results of studies that measured pulpal temperature after diode laser irradiation is used for direct pulp capping before applying a pulp dressing to the exposed pulp have not yet been published.

Diode lasers are now widely used in restorative dentistry, especially for whitening discolored teeth using light-activated bleaching [Eldeniz et al., 2005; Zhang et al., 2007]. Zhang et al. [2007] has recommended that the maximum power output should be 1 W and the exposure time should not exceed 10 seconds when laser irradiation is used for dental bleaching or tooth whitening. In the present study, the lowest output power of the laser diode that we used for laser irradiating the pulp exposure hole was 0.7 W, and the beam was delivered in two 10-second bursts. We found that the resultant elevation in in the pulpal chamber temperature at these operating conditions was not greater than 5.5°C and not significantly different from the rises that were induced by the LCUs. However, we did find that laser irradiation of the pulp exposure hole at output powers of 1 W and 1.5 W caused elevations in the pulpal chamber temperature that were greater than 5.5°C. A 5.5°C rise in pulpal chamber temperature is critical because temperature rises greater than 5.5°C are considered to be sufficient for causing thermal injury to the pulp. Kodonas et al. [2009] measured the pulpal chamber temperature when a diode laser was used at a power output of 2 W and irradiation times of 15 and 30 seconds for bleaching the tooth’s enamel surface. They found that the resultant rise in the pulpal chamber temperature was below this critical temperature of 5.5°C. Ogisu et al. [2008] examined the reaction and hard tissue derivation of rat pulp that was directly capped with adhesive resins after CO₂ laser irradiation. They found that the thickness of the eosophiphic heat denaturation layer and the protein coagulation layer had a tendency to increase as the intensity of laser irradiation increased. Collectively, all these results imply that the rise in pulpal chamber temperature and the occurrence of tissue changes following laser irradiation of a tooth are dependent on the region of the tooth that is to be laser irradiated and the purpose of the irradiation.

Blood flow through pulp tissue is a mechanism for heat dissipation, and this heat may also be absorbed by the gingival connective tissues. It has also been claimed that it is not possible to create an experimental system that can accurately measure heat dissipation in human teeth because of large variations in the thickness of the dentine layer [Aguir et al., 2005]. Accordingly, Santini et al. [2008] commented that the temperature values that are measured in in vitro studies cannot be directly extrapolated to temperature changes that occur in vivo. In the present study, the determination
of the pulp chamber temperatures was done in pulpal chambers that were filled with distilled water, whose temperature was maintained at 24°C. Although the temperature of the water bath in other studies was set at the physiological temperature of 37°C in order to simulate a clinical setting [Shortall and Harrington, 1998; Hanning and Bott, 1999], we used the same temperatures that were used by other investigators [Aguiar et al., 2005; Danesh et al., 2004], namely 24°C, in order to compare our results with theirs. Lastly, our experimental set up did not account for blood flow in the vital pulp chamber and the surrounding tissues.

One of the considerations when choosing the most suitable compound for direct pulp capping is its ability to provide an adequate seal. In the present study, all the compounds that were used for direct pulp capping were found to be effective sealants. On the other hand, laser irradiation of the pulp exposure hole at all test output powers did not result in the creation of an effective seal. In fact, we found laser irradiation of the pulp exposure hole at output powers that were greater than 0.7 W causes cracking and crazing of the dentinal margins of the pulp exposure holes.

References


