©Operative Dentistry, 2018, **43-1,** 71-80

Effect of Light Activation of Pulp-Capping Materials and Resin Composite on Dentin Deformation and the Pulp Temperature Change

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Clinical Relevance

Light curing of pulp-capping materials caused deformation of pulpal dentin and increased pulpal temperature by light curing and exotherm effects. The use of Vitrebond or Ultra-Blend Plus in deep cavities resulted in better performance through a combination of high degree of cure, lower temperature, and dentin strain.

SUMMARY

Objectives: To analyze the effect of pulp-capping materials and resin composite light activation on strain and temperature development in the pulp and on the interfacial integrity at the pulpal floor/pulp-capping materials in large molar class II cavities.

Methods: Forty extracted molars received large mesio-occlusal-distal (MOD) cavity bur preparation with 1.0 mm of dentin remaining at the pulp floor. Four pulp-capping materials (self-etching adhesive system, Clearfil SE Bond [CLE], Kuraray), two light-curing calcium hydroxide cements (BioCal [BIO], Biodinâmica, and Ultra-Blend Plus [ULT], Ultradent), and a resin-modified glass ionomer cement– (Vitrebond [VIT], 3M ESPE) were applied on the pulpal floor. The cavities were incrementally restored with resin composite (Filtek Z350 XT, 3M ESPE). Thermocouple (n=10) and strain gauge (n=10) were placed inside the pulp chamber in contact with the top of the pulpal floor to detect temperature changes and dentin strain during light curing of the pulp-capping materials and during resin composite restoration. Exotherm was calculated by subtracting postcure from polymerization temperature (n=10). Interface integrity at the pulpal

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DOI: 10.2341/16-325-L

floor was investigated using micro-CT (Sky-Scan 1272, Bruker). The degree of cure of capping materials was calculated using the Fourier transform infrared and attenuated total reflectance cell. Data were analyzed using one-way analysis of variance followed by the Tukey test (α=0.05).

Results: Pulpal dentin strains (μs) during light curing of CLE were higher than for other pulp-capping materials ($p<0.001$). During resin composite light activation, the pulpal dentin strain increased for ULT, VIT, and CLE and decreased for BIO. The pulpal dentin strain was significantly higher during pulp-capping light activation. The temperature inside the pulp chamber increased approximately 3.5°C after light curing the pulp-capping materials and approximately 2.1°C after final restoration. Pulp-capping material type had no influence temperature increase. The micro-CT showed perfect interfacial integrity after restoration for CLE and ULT; however, gaps were found between BIO and pulpal floor in all specimens. BIO had a significantly lower degree of conversion than ULT, VIT, and CLE.

Conclusions: Light curing of pulp-capping materials caused deformation of pulpal dentin and increased pulpal temperature in large MOD cavities. Shrinkage of the resin composite restoration caused debonding of BIO from the pulpal floor.

INTRODUCTION

Advanced caries in posterior teeth frequently results in deep cavities that require protection of the dentin–pulp complex tissues. The capping procedure consists of application of a capping material in order to maintain pulp vitality, stimulate pulp and dentin repair, and minimize postoperative sensitivity.[1] Many current pulp-capping materials require light activation, which may result in thermal and shrinkage stress.[1] Subsequent resin composite light-curing activation will cause further thermal and shrinkage effects that may induce enamel microcracks and postoperative sensitivity due to dentin deformation.[2,3]

For deep cavities, the use of pulp capping is a common protocol to prevent postoperative sensitivity.[4] The pulp is a highly vascularized tissue that responds to thermomechanical stimuli.[5] To avoid tissue damage, pulpal temperature and deformation should be limited.[6] The pulp/dentin interface should therefore protect against thermal and electrical effects as well as maintain structural integrity during curing irradiation of restorative materials.[7,8] Various light-curing materials have been used for dentin capping, such as resin-modified glass ionomer cements, self-etching adhesive systems, and calcium hydroxide cement.[9-11]

Few studies have reported the effects of temperature rise and dentin deformation within the pulp chamber due to the curing reaction of the capping material. Therefore, the aim of this study was to evaluate the effect of the light-curing process of capping materials and resin composite on the dentin deformation and the pulp temperature change in deep class II mesio-occlusal-distal (MOD) restorations. The null hypothesis was that the capping material and resin composite filling technique had no effect on the dentin deformation and temperature change in the pulp chamber.

METHODS AND MATERIALS

Tooth Selection and Cavity Preparation

Eighty extracted intact caries-free human molars were used in this study (Ethics Committee in Human Research approval no. 06257012.1.0000.5152). The teeth were selected to have an intercuspal width within a maximum deviation of 10% from the determined mean.[12] The intercuspal width varied between 4.8 and 5.9 mm. The roots were sectioned 5.0 mm below the cementum–enamel junction using a precision saw (Isomet 1000, Buehler, Lake Bluff, IL, USA). The pulp chamber was manually accessed with a spherical diamond bur (#1016 HL, KG Sorensen, Barueri, SP, Brazil) in a high-speed hand piece with copious air–water spray, preventing damage to the pulp dentin above the pulp chamber (Figure 1). To simulate bone support, the teeth were embedded in a polystyrene resin (Cristal, Piracicaba, SP, Brazil) up to 2 mm below the cementum–enamel junction. The teeth were cleaned using a rubber cup and fine pumice water slurry. Class II MOD cavities with four-fifths of the intercuspal width and 4-mm depth were prepared using a cylindrical-with-round-end diamond bur (#3099, KG Sorensen) with copious air–water spray using a cavity preparation machine (Figure 1).[13] This machine consisted of a high-speed hand piece (Extra Torque 605 C, Kavo do Brasil, Joinville, SC, Brazil) coupled to a mobile base. The mobile base moves vertically and horizontally with three precision micrometric heads (152-389, Mitutoyo Sul Americana Ltda, Suzano, SP, Brazil), attaining a 2-μm level of accuracy (Figure 1). The 1.0-mm-thick remaining pulp dentin was verified using an X-ray image (Kodak Dental Systems, Carestream Health, Rochester, NY, USA).

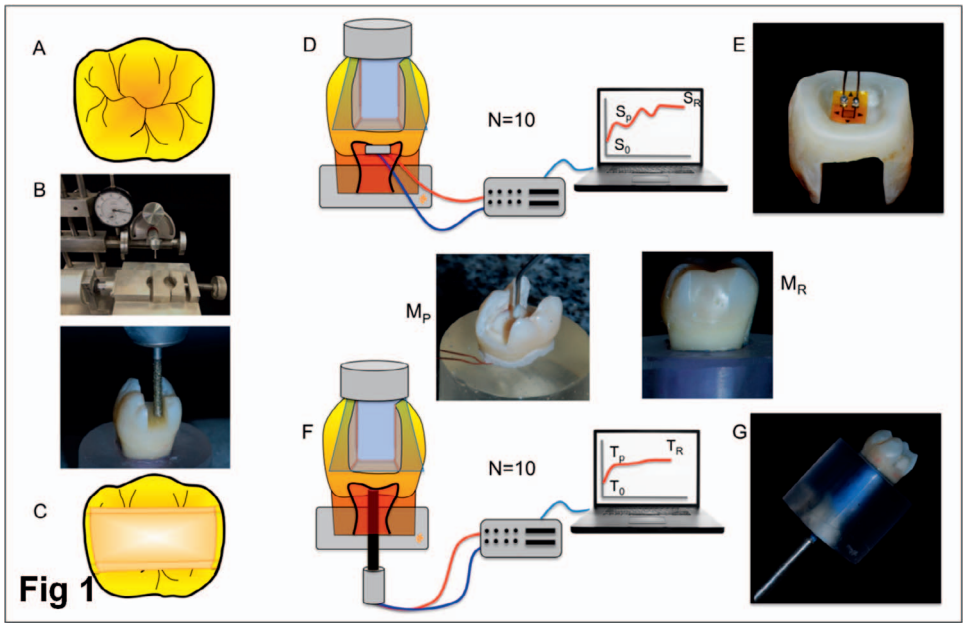

Figure 1. *Schematic diagram of study design. (A): Intact molar. (B): Cavity preparation machine. (C): Mesio-occlusal-distal deep cavity preparation. (D): Measurement of deformation of pulp floor dentin at M_P (pulp capping) and M_R (final restoration). (E): Strain gauge bonded to pulp inner dentin. (F): Measurement of pulpal dentin temperature at M_P (pulp capping) and M_R (final restoration). (G): Thermocouple inserted into the pulp chamber contacting the pulp inner dentin.*

Temperature Rise Measurement

Forty of the prepared teeth were used for temperature rise measurement (n=10/group). A J-type thermocouple (5TC-TT-J-40-36, Alutal Siebeck Sensors, São Paulo, SP, Brazil) was inserted into the pulp chamber through a root perforation, maintaining contact with the pulp–dentin floor above the pulp chamber (Figure 1). The thermocouple was made of iron and constantan alloys (Cu 55%+Ni 45%) represented by two terminals: a positive pole with a white end and a negative pole with a red end. Externally, the thermocouple was coated with black rubber and an active circular tip (1.0-mm diameter). The J-type thermocouple could capture temperature variations ranging from −20°C to +800°C with a ±0.2°C accuracy. The thermocouple was connected to a data acquisition device (ADS2000IP, Lynx Technology, São Paulo, SP, Brazil). The data were transferred to a computer, using acquisition signal transformation by data analysis software (AqDados 7.02 and AqAnalisys, Lynx). The temperature value was recorded at 0.25-second intervals to detect temperature changes during the light irradiation of the pulp capping of four materials: self-etching adhesive system (Clearfil SE Bond [CLE], Kuraray, Osaka, Japan), light-curing calcium hydroxide cement (BioCal [BIO], Biodinâmica, Ibiporã, PR, Brazil), light-curing calcium hydroxide cement (Ultra-Blend Plus [ULT], Ultradent, South Jordan, UT, USA), and resin-modified glass ionomer cement (Vitrebond [VIT], 3M ESPE, St Paul, MN, USA). The capping material information is shown in Table 1. For the CLE group, the primer was applied followed by gentle air spray, then the adhesive was applied and irradiated for 20 seconds using a QTH light-curing unit with 550-mW/cm^2 output (Demetron 501, Kerr, Orange, CA, USA). For ULT, BIO, and VIT groups, the capping materials were manipulated and inserted in a 1.0-mm-thick layer and irradiated using the QTH light-curing unit. The MOD cavity was filled with a restorative resin composite (Filtek Z350 XT, 3M ESPE; see Table 1) using eight increments, each light cured for 20 seconds using the QTH light from the occlusal direction with the tip placed as close as possible to the cavity.

Exotherm of Pulp-Capping Material

The exotherm temperatures of the light-cured capping materials were determined in a separate experiment, where the materials were placed directly on top of a custom thermocouple tip (n=10). To standardize the amount and contain the capping material, transparent adhesive tape (Durex, 3M ESPE) was placed around the 3.0-mm circular custom-made brass tip of a J-type thermocouple (5TC-TT-J-40-36, Alutal Siebeck Sensors), creating a 1-mm-tall "container" (Figure 2).[14] The capping material was inserted into the container, and the light-curing tip was positioned 1.0 mm above it. The capping material was irradiated for 20 seconds using the QTH light-curing unit. Temperature changes were recorded during the curing run and during a second 20-second irradiation run with the cured material. Exotherm temperature (T_r) was deter-

Table 1: *Restorative Materials Used in the Study*

Material Type	Commercial Name	Manufacturer	Composition
Resin-modified glass ionomer	Vitrebond	3M ESPE (St Paul, MN, USA)	Powder: fluoroaluminosilicate glass powder with SiO_2, AlF_3, ZnO, SrO, cryolite, NH_4F, MgO, and P_2O_5; liquid: modified polyacrylic acid with pendant methacrylate groups, HEMA, water, and photoinitiator
Light-curing calcium hydroxide cement	Ultra-Blend Plus	Ultradent Products, Inc (South Jordan, UT, USA)	Urethane dimethacrylate (58%), calcium hydroxide (10%)
Light-curing calcium hydroxide cement	BioCal	Biodinâmica (Ibiporã, PR, Brazil)	Calcium (3.53%), ethylene urethane dimethacrylate, inorganic fillers, barium sulfate, photoactivator, titanium dioxide, and iron oxide
Self-etching adhesive system	Clearfil SE Bond	Kuraray Medical, Inc (Okayama, Japan)	Primer: MDP, HEMA, hydrophilic dimethacrylate,N,N-diethanol-p-toluidine, water; bonding: MDP, Bis-GMA, HEMA, hydrophobic dimethacrylate, dl-camphorquinone,N,N-diethanol-p-toluidine, and silanated silicate
Nanofilled resin composite	Filtek Z350XT	3M ESPE	Bis-GMA, Bis-EMA, UDMA, TEGDMA, silica and zirconia nanofillers, and agglomerated zirconia-silica nanoclusters

Abbreviations: Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; Bis-GMA, bisphenol-A diglycidyl ether dimethacrylate; HEMA, 2-hydroxyethylmethacrylate; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

mined by subtracting the temperature rise of the second run (T_{p1}, which represented the thermal change due to irradiation only) from the first (T_{La}, which contained both irradiation and exotherm contributions): $T_r = T_{La} - T_{p1}$ (Figure 2).

Pulpal Dentin Deformation

The other 40 prepared teeth were used for the determination of pulp–dentin deformation (n=10 per group). Pulp deformation was measured with strain gauges (PA-06-038AA-120LEN, Excel Sensores, Embú, SP, Brazil), which had an internal electrical resistance of 120 Ω, a gauge factor of 2.07, and a grid size of 1 mm^2. The strain gauge was attached to the pulpal dentin above the pulp chamber (Figure 1). For the strain gauge attachment, the teeth were sectioned 1 mm below the cemento–enamel junction using a precision saw (Isomet 1000, Buehler). The dentin located above the pulp chamber was etched with 37% phosphoric acid for 15 seconds, rinsed with an air–water spray, and air-dried. The strain gauge was fixed using cyanoacrylate adhesive (Super Bonder, Loctite, Gulph Mills, PA, USA) (Figure 1). The strain gauges were placed consistently in the buccal-lingual direction to standardize the strain measurement. In addition, a second strain gauge was fixed to another intact tooth to compensate for dimensional deviations due to temperature effects. The strain gauges were connected to a data acquisition device (ADS2000IP, Lynx). Strain values were recorded at 0.25-second intervals during the light irradiation of the pulp-capping materials and the restorative procedure.

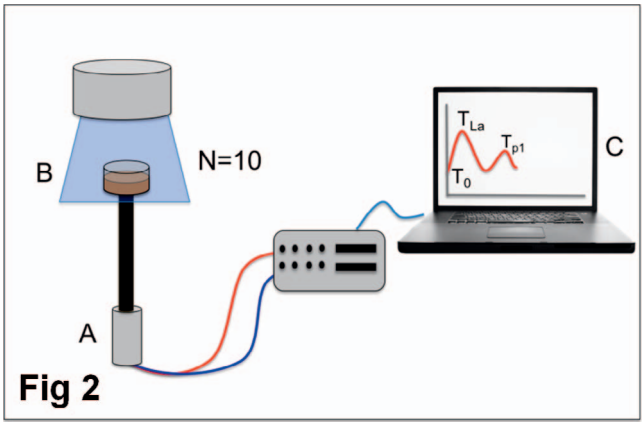

Figure 2. *Schematic diagram of test design to measure temperature increase and exotherm of capping materials. (A): Thermocouple. (B): Light-curing source positioned 1.0 mm from the capping material. (C): Temperature recorded at T_0 (temperature before the light activation). T_{La}, maximum temperature reached during the light activation of capping material; T_{p1}, temperature measured at two minutes after 20 seconds of light activation.*

Pulp-Capping Material Interface Integrity

To verify the integrity between capping material and the pulp–dentin floor, micro-CT analyses were performed after the final restoration (SkyScan 1272, Bruker microCT, Kontich, Belgium). The crowns were mounted on a custom attachment and scanned in the micro-CT scanner. The X-ray scanner

contains an X-ray microsource, an X-ray detector (chamber), an object handle for positioning and rotating the sample during the tomographic acquisition, and associated electronics to power the X-ray source and the chamber. The scanner operated at 100 kV and 111 mA (0.11-mm Cu filter). The resolution used was 1224/820 pixels (15 μm). The scanning was performed by 180° rotation around the vertical axis with a rotation step of 0.5, average image acquisition 3, position height of 30 mm inside the apparatus, and 35 minutes of scanning time. Images of each specimen were reconstructed (NRecon version 1.6.10.1, Bruker microCT), providing axial cross sections of their inner structure, and the same gray ranking for all samples was selected with the standard minimum of 0 and a maximum of 0.19635. No image correction was performed. The reconstructed samples were saved in bitmap format. Then, using DataViewer software (Bruker microCT), all samples were visualized to check acquisition quality. CTAn version 1.13 software (Bruker microCT) was used for the three-dimensional (volume, surface area, and structure model index) evaluation. CTVol version 2.0 software (Bruker microCT) was used for visualization and qualitative evaluation of the specimens.

Degree of Conversion of Pulp-Capping Material

The degree of conversion (DC) of capping materials (n=10) was assessed using Fourier transform infrared (FTIR) spectroscopy (Vertex 70, Bruker Optik GmbH, Ettlingen, Germany) with attenuated total reflectance crystal sampling, mid-infrared, and deuterated triglycine sulfate detector elements (Bruker Optik). Capping material in a similar amount as used in the prepared tooth cavities was inserted on the crystal sensor of the FTIRs. The spectra were obtained between aromatic C=C bond stretching vibrations (1608 cm^{-1}) and aliphatic C=C bond stretching vibrations (1638 cm^{-1}), with 4-cm^{-1} resolution and 32 scans coaddition. All analyses were performed under controlled temperature (25±1°C) and humidity (60%±5%) conditions. DC was calculated from the equivalent aliphatic (1638 cm^{-1}) aromatic (1608 cm^{-1}) molar ratios of cured (C) and uncured (U) CLE and BIO capping materials. For the VIT, the reference peak was the ester bonds (1712 cm^{-1}), and for the Ultra-Blend, the reference peak was the carbonyl (1720 cm^{-1}), due to the absence of the aromatic carbon bond. The formula to calculate the DC was $DC(\%) = (1 - C/U) \times 100$.

Table 2: *Means (Standard Deviation) of Maximum Temperature Change (°C) at Dentin Floor of the Pulp Chamber During Pulp Capping and Resin Composite Restoration Polymerization (n=10)*[a]

Materials	Pulp/Dentin Capping	Cumulative at Final Restoration
BioCal/Z350XT (BIO)	4.0 (0.4) A	6.7 (0.8) A
Ultra-Blend Plus/Z350XT (ULT)	3.9 (0.4) A	6.6 (0.3) A
Vitrebond/Z350XT (VIT)	3.8 (0.4) A	6.2 (0.6) A
Clearfil SE Bond/Z350XT (CLE)	6.4 (0.8) B	8.8 (0.6) B

[a] *Different letters in columns indicate significant difference among capping materials for each moment of measurement (p<0.05).*

Statistical Analyses

The data of pulpal temperature rise, pulp dentin strain, exotherm temperature, and DC of capping materials were analyzed for normal distribution and homoscedasticity using the Shapiro–Wilk test and the Levene test, respectively. One-way analysis of variance (ANOVA), followed by the Tukey test, was used for comparing capping materials. All tests were performed at a significance level of $\alpha = 0.05$, and all analyses were performed using the Sigma Plot version 13.1 statistical package (Systat Software Inc, San Jose, CA, USA). The gap formation was analyzed descriptively.

RESULTS

Temperature Rise Measurement

The means and standard deviations of the maximum temperature change at the dentin floor for all groups are presented in Table 2. A significant effect was observed for interaction between capping material and temperature increase during the restoration ($p<0.001$). During the light activation of the capping material and the final restoration, the light curing of the CLE resulted in a higher temperature change than other materials ($p=0.021$). No difference was observed among BIO, ULT, and VIT ($p=0.712$). The temperature change was significantly higher during the light activation of pulp capping than during the incremental filling. The means and standard deviations of the temperature change variation measured during the resin composite filling only (calculated as final temperature change minus temperature change at pulp capping) for all groups are presented in Figure 3. No significant difference was observed in temperature change after light activation during the incremental filling procedure among the capping material groups ($p=0.321$).

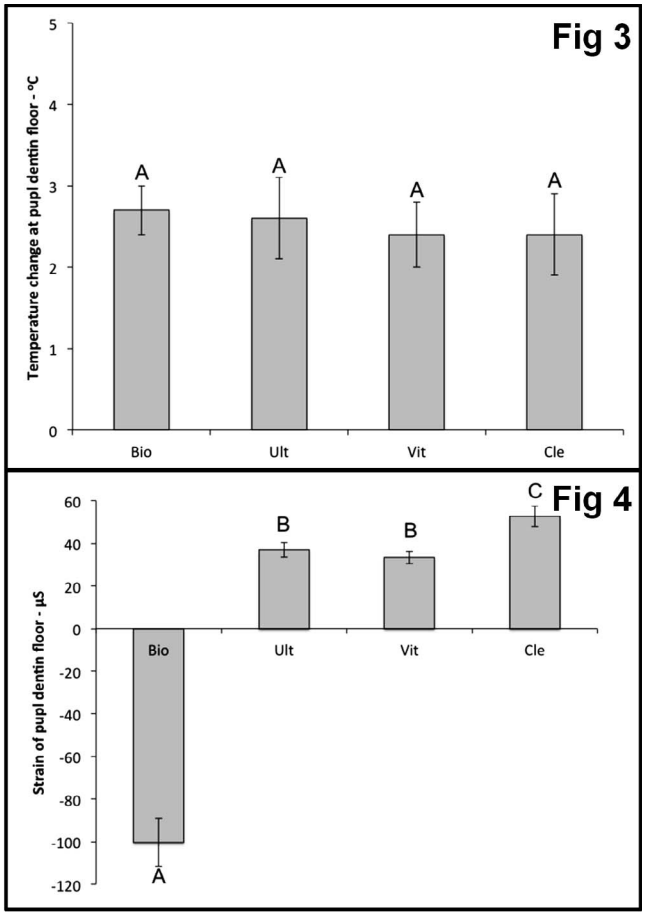

Figure 3. *Temperature changes at pulp dentin floor (°C) measured during resin composite placement (final temperature change – pulp capping temperature change). Different uppercase letters indicate significant difference among capping materials for each moment of measurement (*p*<0.05).*

Figure 4. *Strain values at pulp dentin floor (μs) measured during resin composite placement (total strain – pulp-capping strain values). Different uppercase letters indicate significant difference among capping materials (*p*<0.05).*

Pulp–Dentin Deformation

The means and standard deviations of the maximum strain at the pulp–dentin floor for all groups are presented in Table 3. A significant effect was observed for interaction between capping material and moment of the restoration ($p<0.001$). During the light activation of the capping material, CLE resulted in higher strains at the pulp–dentin floor than the other materials ($p=0.010$). No difference was observed among BIO, ULT, and VIT ($p=0.124$). After the incremental filling, BIO had the lowest and CLE the highest strains at the pulp–dentin floor of all groups ($p<0.001$). No difference was found between ULT and VIT ($p=0.802$). The means and standard deviations of the strain in dentin due to the restoration filling only (final strain value minus strain values measured during pulp capping) for all groups are presented in Figure 4. BIO had the lowest and CLE the highest strain of all groups ($p<0.001$). No difference was found between ULT and VIT ($p=0.707$).

Table 3: *Means (Standard Deviation) of Maximum Strain (μs) in Dentin Floor of the Pulp Chamber During Pulp Capping and Resin Composite Restoration Polymerization (n=10)*[a]

Materials	Pulp/Dentin Capping	Cumulative at Final Restoration
BioCal/Z350XT (BIO)	183.9 (44.3) A	83.5 (28.3) A
Ultra-Blend Plus/Z350XT (ULT)	179.9 (55.4) A	216.9 (45.7) B
Vitrebond/Z350XT (VIT)	176.4 (56.3) A	210.3 (42.1) B
Clearfil SE Bond/Z350XT (CLE)	215.4 (60.6) B	268.1 (46.6) C

[a] *Different letters in columns indicate significant difference among capping materials for each moment of measurement (*p*<0.05).*

Exotherm of Pulp-Capping Material

Temperatures increased during light activation. The means and standard deviations of the maximum peak temperature are shown in Table 4. One-way ANOVA showed significant differences among the temperature increases ($p<0.001$) and among the exotherm values ($p<0.001$). The CLE had significantly higher temperature increases than all other capping materials. No difference was found between ULT, BIO, and VIT regardless of the testing moment.

Pulp-Capping Material Interface Integrity

The micro-CT images showed gaps between restoration and the pulp–dentin floor caused by detachment of the BIO (Figure 5A). Perfect integrity between the restoration and the pulp–dentin floor was observed for all other groups (Figure 5B,C,D).

Table 4: *Means (Standard Deviation) of Maximum Temperature Increases (°C) and Exotherm (Mean ± Standard Deviation) for Capping Materials (n=10)*[a]

Capping Material	Temperature Increases (°C)	Exotherm (°C)
Clearfil SE Bond (CLE)	29.0 (2.4) A	16.8 (1.8) A
Ultra-Blend Plus (ULT)	14.6 (1.2) B	8.1 (1.8) B
Vitrebond (VIT)	17.5 (3.3) B	8.9 (3.6) B
BioCal (BIO)	18.2 (2.0) B	9.8 (2.4) B

[a] *Different letters in columns indicate significant difference among capping materials for each moment of measurement (*p*<0.05).*

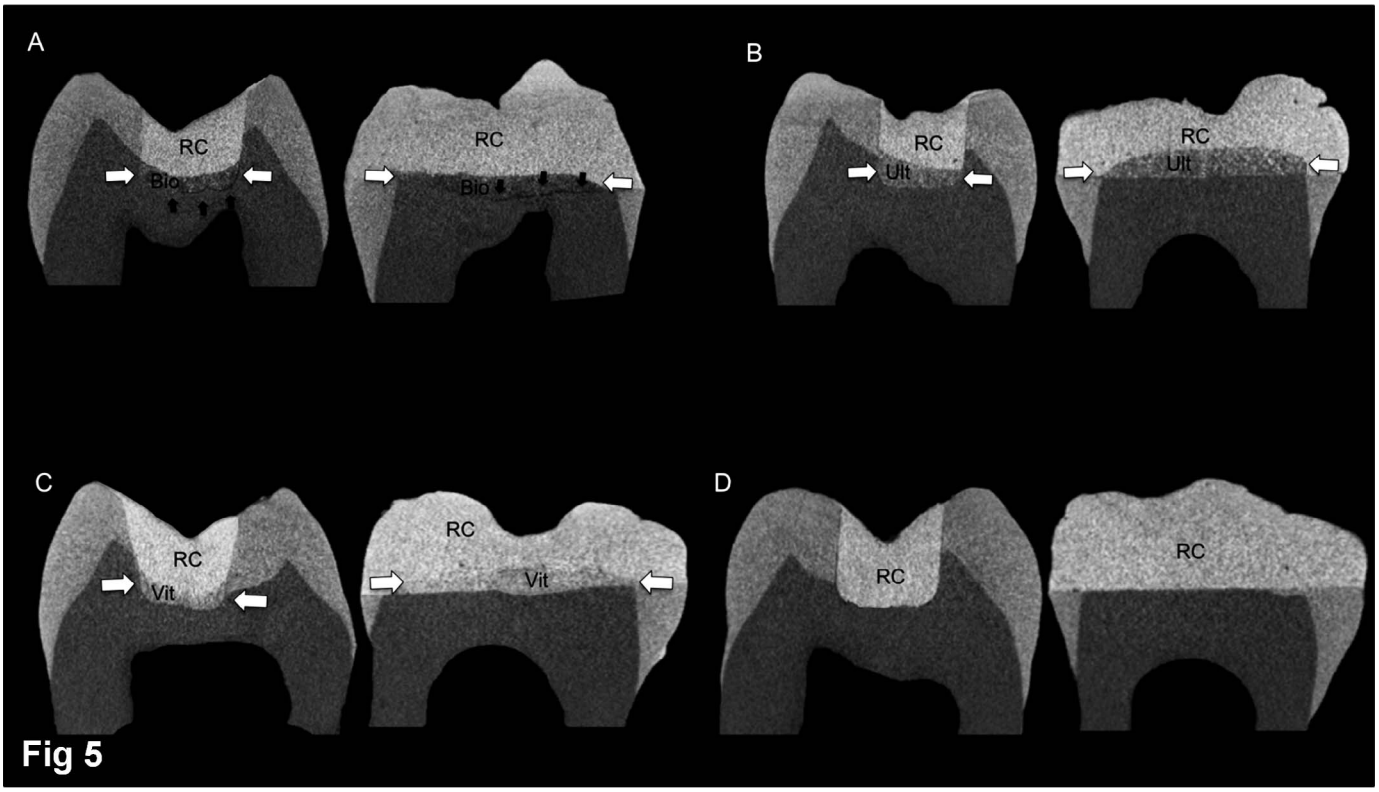

Figure 5. *Micro-CT images of the molar restorations. (A): BIO/Z350XT group (black arrow indicates gap between BioCal and pulp floor dentin). (B): ULT/Z350XT group. (C): VIT/Z350XT group and CLE/Z350XT group (white arrows on A, B, and C indicate pulp protection material layers).*

Degree of Conversion of Pulp-Capping Material

The means and standard deviations of the degree of cure for all capping materials are shown in Figure 6. One-way ANOVA showed significant difference among the degree of cure (p=0.012). The BIO had a significantly lower degree of cure than all other capping materials. No difference was found among ULT, VIT, and CLE.

DISCUSSION

The null hypothesis was rejected; the light activation of capping material and the resin composite incremental filling technique caused dentin deformation and temperature changes in the pulp chamber. The biomechanical behavior of restorative materials is important in understanding restorative procedures.[15] Light-curing materials produce temperature rises that are influenced by factors such as intensity of light, composition and transmission properties of resin composites, exotherm reaction, depth of the cavity and restoration, duration of light exposure, and type of light source.[16] Thermal stimuli applied externally have been shown to result in rapid development of strains before a change in temperature is detected at the pulp surface.[6]

Particularly in deep cavities, the amount of remaining dentin thickness, the type of pulp-capping materials, and their degree of cure can affect heat generation during restorative procedures, which could lead to irreversible pulpal damage.[17] Temperature increases originate from the exothermic reaction during the curing process of the material and the energy absorbed from the light-curing unit.[18] In this study, we measured the exotherm and the temperature increases during the application of the capping materials. A limitation of this study may be the absence of the pulpal fluid and pulpal pressure, which can reduce the effect of temperature rise inside the pulp chamber. Presence of pulpal fluid may also exacerbate the dentin strain because the humidity makes dentin more prone to deformation.[19]

In this study, we tested a resin-modified glass ionomer cement, a self-etching adhesive system, and two light-curing calcium hydroxide cements. The self-etching adhesive system proved to be the material that blocked the least amount of heat coming from the light used for the activation of the pulp-capping material, maybe because it was the thinnest layer.

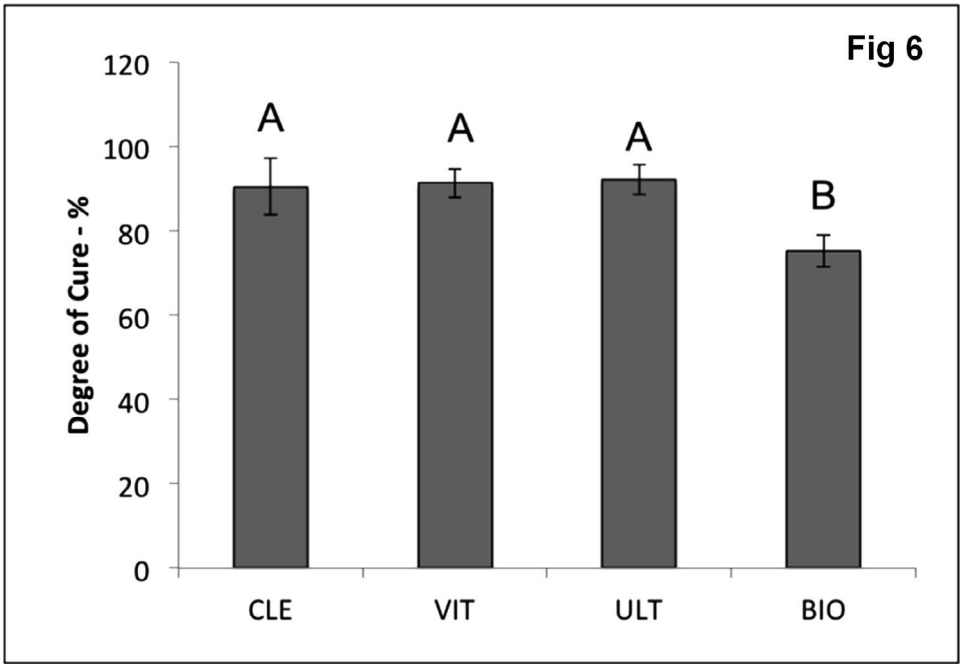

Figure 6. *Means and standard deviations for degree of cure (n=5) for capping materials. BIO, BioCal; ULT, Ultra-Blend Plus; VIT, Vitrebond; CLE, Clearfil SE Bond. Different uppercase letters indicate significant difference among capping materials (*$p<0.05$*).*

Additionally, the higher exotherm of the adhesive system may contribute to the higher temperature values at the pulp surface. Despite its popularity, the physical properties of conventional calcium hydroxide cement, such as water solubility, the absence of bond strength to dental hard tissues, and low compressive strength, have limited its use.[20] Light-curing pulp-capping materials have been developed to avoid such disadvantages and to extend the working time. The light-curing calcium hydroxide cements (BIO and ULT) and the resin-modified glass ionomer cement (VIT) had similar temperature increases when they were light activated and similar exotherms that were lower than the adhesive system. The thickness of these materials and their opacity may also help reduce the heat transfer during the following restoration procedure with the resin composite.

The cumulative temperature rises at the pulp–dentin floor during the incremental filling procedure showed that the final restoration temperature rise was similar for all the materials. This result indicates that the resin-modified glass ionomer cement or light-curing calcium hydroxide cement were not more effective in preventing pulp temperature increases than the adhesive system and that the capping material could not prevent the temperature rise in the pulp during polymerization of the resin composite. The use of the capping materials should thus be determined by the necessity to prevent biologic damage of pulp tissues and stimulate dentin and pulp repair.[21-23] Capping materials require a high degree of cure to prevent complications in pulp response.[24,25] Especially in deep cavities, the proximity of capping material to pulp tissue and the higher permeability of the deep dentin may result in free nonconverted monomers ending up in pulp tissues.[26] The BioCal, which is expected to be a "stimulating capping material" resulting in dentin neo-formation by calcium hydroxide composition, had a lower DC with 25% of the uncured monomers. This lower DC warrants further study for the use of this material in deep cavities due to a potential toxicity effect from uncured monomers.

Strain gauges were used for measuring the deformation inside the pulp. These deformations are caused by thermal and volumetric changes that take place in the capping materials and resin composite during polymerization. The higher deformation at the pulpal dentin wall that was found when the CLE was light activated can probably be attributed to the higher heating and thus higher thermal expansion. When we separately evaluated the variation of the strain values at the pulp–dentin floor during the resin composite placement, the BIO showed negative deformation values. These indicate compression force. Apparently, the material deformation was not transferred to the remaining dentin walls. The micro-CT images showed gaps between the restoration and the pulp–dentin floor caused by detachment of the BioCal at the final stage of the restoration. This may be explained by the high polymerization shrinkage of BIO that could have

caused detachment of the pulpal wall and the absence of adequate bonding interaction between BIO and dentin. Perfect integrity between the restoration and the pulp–dentin floor was observed for all other groups.

In this study, a QTH light was used for light activation of the materials. For the incremental filling in eight increments, each light cured for 20 seconds, the light curing resulted in 88 J/cm^2 of total energy delivered ($8\times20\times550\ 10^{-3}$). Irradiance and temperature values at the light guide tip vary per light-curing unit, and therefore temperatures at the pulpal floor are also likely to vary.[27,28] The choice of restorative resin composite (resin composite type and filling technique) is another variable that can affect the temperatures.[29] Since temperature rise and dissipation are affected by various interacting properties, further study is needed to determine the thermal response to other types of light-curing units and for restorative resin composites with different optical properties or filling techniques (eg, bulk-fill resin composites).

This study did not find significant differences in pulp–dentin deformation among all BIO, VIT, and ULT groups. No power analysis was performed to determine sample size, which was a limitation of this study. An increased sample size may be needed to detect potential differences among these groups. However, it should be noted that not all statistically significant differences are clinically relevant. From a clinical perspective, the present study demonstrated that capping material can reduce initial heating and strain on the pulpal dentin floor, thought to be the main cause of pulpal sensitivity. However, pulp-capping materials had no effect on temperature rise and deformation at the pulpal roof caused by the resin composite restoration. In general, the use of capping material is recommended only for deep cavities where the dentin remaining at the pulpal floor is not sufficient to prevent temperature rise and dentin strain.[23,30] The tested materials should be adequately polymerized to prevent future damage of pulp tissue by unreacted monomers.[20,31] The performance of BIO demonstrated that this material cannot be used in deep cavities. Therefore, when a capping material is necessary for deep cavities, a resin-modified glass ionomer may be the best option that combines good biocompatibility[9] and biomechanical performance.

CONCLUSIONS

Within the limitations of this *in vitro* study, we can conclude that the light curing of pulp-capping materials caused pulp–dentin deformation and increased pulpal temperature. BioCal demonstrated a lower degree of cure and a lower capacity to maintain contact with the pulpal floor after shrinkage of the resin composite restoration. Vitrebond and Ultra-Blend Plus demonstrated a better combination of strains and temperature changes at the pulpal surface.

Acknowledgements

This project was funded by grants from the CNPq—National Council for Scientific and Technological Development from CAPES and FAPEMIG. This research was performed at CPbio-Biomechanics, Biomaterials, and Cell Biology Research Center, Federal University of Uberlândia.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Ethics Committee in Human Research approval, Federal University of Uberlandia. The approval code for this study is 06257012.1.0000.5152.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 7 March 2017)

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