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The effect of resin composite pre-heating on monomer conversion and polymerization shrinkage

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ABSTRACT

Objectives. To determine monomer conversion and polymerization shrinkage of a resin composite after different pre-heating procedures and storage intervals.

Methods. For a commercial resin-based composite the immediate (5 min) and final (24 h) degree of conversion was measured on top and bottom surfaces utilizing FTIR spectroscopy. Composite pre-heating temperatures were selected between 10 and 68 °C. Polymerization shrinkage was measured according to Archimedes' principles of buoyancy after 5 min at respective pre-heating temperatures and after 24 h dark and wet storage at 37 °C. Intra-cavity temperature development was monitored using a K-type thermocouple.

Results. No significant increase in immediate as well as in final degree of conversion were measured from composite pre-heating at 68 °C compared to 54 and 39 °C. Linear correlations were detected immediately after photo-polymerization and on the top surface after 24 h storage. Polymerization shrinkage as a function of pre-heating temperatures exhibited a linear correlation after 5 min, but no statistically different behavior after 24 h.

Significance. Pre-heating of resin composites does not increase degree of conversion over time. It can be clinically beneficial, due to a superior marginal adaptation. This advantageous effect of reduced material paste viscosity has to be clinically addressed, since temperature rapidly drops to the physiological level upon removal from the pre-heating device.

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1. Introduction

Directly placed composite resins serve as standard materials in restorative and esthetic dentistry. Their chemistry and properties have been extensively investigated in the relevant dental literature [1,2]. The clinical success of a composite restoration is closely related to the material characteristics like polymerization shrinkage, degree of conversion and mechanical properties [3–5]. Handling characteristics like paste viscosity, packability, stickiness and polishability play a critical role, as well [6]. To receive a perfectly sealed, long-

lasting restoration, material adaptation to the cavity walls is of importance [7].

Recently, pre-heating resin composites with appropriate devices have been advocated as a method to reduce paste viscosity, improve marginal adaptation and monomer conversion, and to shorten curing times [8]. Elevated temperatures have been shown to strongly influence composite conversion and mechanical properties, but on the other side to increase the possibility of pulp necrosis [9,10]. Light-curing of methacrylate monomers results in a highly crosslinked structure, with residual unsaturation in the form of pen-

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dant methacrylate groups, due to steric hindrance [3,11]. The degree of conversion, defined as the percentage of reacted C=C bonds, affects several parameters including mechanical properties, solubility, dimensional stability, color change and biocompatibility of resin composites [4,5,12]. In diffusion controlled resin networks, mobility of monomers and polymerization reactivity is increased at elevated temperatures; moreover, under these conditions, the autodeceleration stage of the polymerization reaction can be delayed. Both these contribute to increased monomer conversion [9,13,14]. Indeed, significantly increased monomer conversion after external composite heating at 54 °C compared to room temperature has been reported [15]. Nevertheless, it has been observed, that the higher the degree of conversion in resin composites, the higher is the polymerization shrinkage [4]. In addition, since resin composites exhibit a six to eight times greater thermal expansion than the surrounding tooth structures [16], polymerization contraction along with thermal contraction might create high interfacial stresses in pre-heated composites upon thermal equilibrium, with detrimental effects on marginal adaptation, integrity and seal [17,18].

Commercially available pre-heating devices are operating at a temperature range of 54–68 °C, which is questioned regarding pulp compatibility in deep cavities. Nevertheless, only a 0.8 °C temperature increase was found after placement of a 60 °C heated composite, but a 5 °C increase upon 20 s light-curing [10].

The aim of the present study was to assess the monomer conversion, polymerization shrinkage and intra-cavity temperature profiles of a resin composite after different pre-heating procedures and storage intervals. The null-hypothesis tested was that pre-heating of a resin composite results in improved immediate and 24 h monomer conversion over time, without affecting polymerization shrinkage.

2. Materials and methods

2.1. Material

The visible light-curing dental restorative Tetric® EvoCeram (Lot: H35663, A3 shade, Ivoclar, Vivadent, Schaan, Liechtenstein) was used in this study. The material is based on a bisphenol glycidyl dimethacrylate (BisGMA)/urethane dimethacrylate (UDMA)/triethylene glycol dimethacrylate (TEGDMA) resin matrix, with camphoroquinone as photoinitiator and 82.5 mass% filler content (48.5% inorganic and 34% pre-polymerized fillers). The material was used in syringes and stored at the respective pre-heating temperatures for 30 min. Light-curing was performed using a quartz tungsten halogen unit (Elipar® TriLight, 3M/ESPE, Seefeld, Germany, 800 mW/cm² emitted light intensity) operated in standard mode.

2.2. Dentin temperature profile

Human dentin discs with a thickness of 2 mm were prepared from the coronal sections of freshly extracted human molars. A cylindrical cavity was drilled into the top disc while a K-type thermocouple was embedded in the bottom disc. The

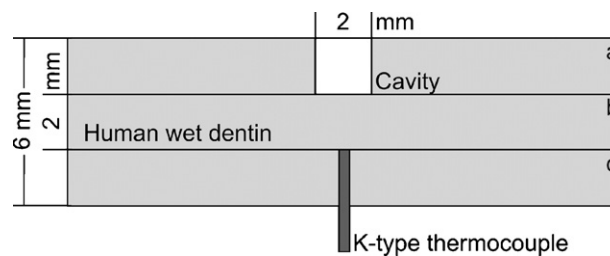


Fig. 1 – Temperature measurement principles.

discs were frictionally laminated according to Fig. 1 and stored at 37 °C in 100% relative humidity for a minimum of 30 min. The resin composite specimens were temperature controlled at 10 ± 2, 23 ± 2, 39 ± 2, and 68 ± 2 °C employing a refrigerator or a dry-heat oven and immediately placed in the dentin cavity at 37 °C. After a 60 s period, to simulate intraoral handling, the fillings were light-cured for 20 s. Temperature was measured at the bottom of the cavity or at a 2 mm distance (an additional specimen series for the 68 °C pre-heated group) by inserting a third sandwich dentin disc. A software controlled temperature datalogger (Voltcraft, Hirschau, Germany) with an accuracy of ±0.3% served to monitor dentin temperature. Mean temperature profiles were calculated from three measurements of each composite temperature group.

2.3. Degree of conversion

Materials and molds were stored and polymerized at temperatures of 10 ± 2, 23 ± 2, 39 ± 2, 54 ± 2 and 68 ± 2 °C. Rectangular composite specimens (6 mm × 4 mm × 2 mm, n = 5) were produced by light-curing from only one direction in order to prepare specimens for surface and in-depth measurements. Specimens were subsequently transferred to a dry-heat oven and stored at 37 °C for 5 min or 24 h prior to DC measurements.

Degree of conversion of the specimens was measured by Fourier transform infrared micromultiple internal reflectance spectroscopy (FTIR). An FTIR spectrometer (Spectrum GX, Perkin-Elmer, Beaconsfield, Bacon, UK) was used, equipped with a micromultiple internal reflectance cell operated under the following conditions: 4000–400 cm⁻¹ range, 4 cm⁻¹ resolution, 50 scans coaddition, 45° para KRS-5 minicrystal (10 mm × 5 mm × 1 mm) of seven internal reflections. Spectra were acquired from top and bottom surfaces. The degree of conversion (% DC) on the tested surfaces was calculated by the two frequency technique using the net peak absorbance areas of the aliphatic C=C stretching vibrations at 1638 cm⁻¹ as analytical frequency and the aromatic C··C stretching vibrations at 1608 cm⁻¹ as reference frequency according to the equation:

$$\%DC = \left(1 - \left(\frac{A_M(C \cdot \cdot C) \cdot A_P(C=C)}{A_M(C=C) \cdot A_P(C \cdot \cdot C)} \right) \right) \times 100 \quad (1)$$

where A_M and A_P represent the net peak absorbance height ratios of the uncured and cured material, respectively.

Statistical analysis was performed employing three-way ANOVA to assess interactions between the independent factors site (top/bottom), storage time (5 min/24 h), and pre-heating temperatures on the % DC. Student–Newman–Keuls

multiple range test was used for multiple comparisons ($\alpha = 0.05$). Regression analysis among the pre-heating temperatures and the corresponding % DC per site and storage time was performed as well. Statistical analysis was calculated using SPSS 15.0 for Windows software (SPSS Inc., Chicago, IL, USA).

2.4. Polymerization shrinkage

Material syringes and buoyancy medium (dist. water containing 0.01% sodium laurylsulfate) were temperature controlled at selected temperatures of 10 ± 2 , 23 ± 2 , 39 ± 2 , and 68 ± 2 °C. The density determination kit was installed on a high accuracy balance (YDK01 and CP124S, Sartorius, Goettingen, Germany) to measure material densities of the uncured (ρ_u) vs. cured (ρ_c) samples according to Archimedes' principles of buoyancy. Densities of the uncured pastes (1 g, $n = 6$) were determined at respective temperatures measuring weight in air vs. in buoyancy medium. Densities after light-curing (0.5 g, $n = 12$) were measured at respective pre-heating temperatures after 5 min or after 24 h storage in H₂O at 37 °C. For calculation of material densities, literature reference was taken for the buoyancy medium densities at respective temperatures [19]. The volumetric polymerization shrinkage (PS; vol.%) was calculated using the equation:

$$PS = \left(\frac{\rho_c - \rho_u}{\rho_c} \right) \times 100 \quad (2)$$

PS data were statistically treated using one-way ANOVA plus the mod. LSD post hoc routine ($\alpha = 0.05$).

3. Results

3.1. Dentin temperature profiles

Fig. 2 shows the dentin temperature profiles following composite pre-heating, placement in dentin cavities at 37 °C and light-curing after 60 s. A maximum temperature increase of 1.3 °C was recorded after immediate application of the 68 °C pre-heated resin composite, whereas a maximum decrease of 2.2 °C was observed after placement of the 12 °C cooled material. However, at the beginning of the irradiation period (60 s

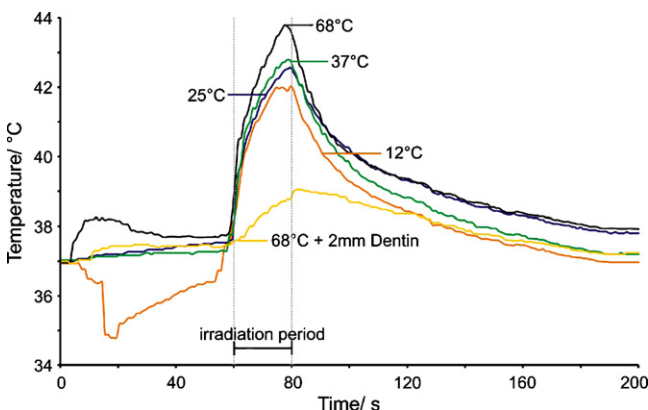


Fig. 2 – Representative temperature profiles after placement of pre-heated composites in experimental dentin cavities.

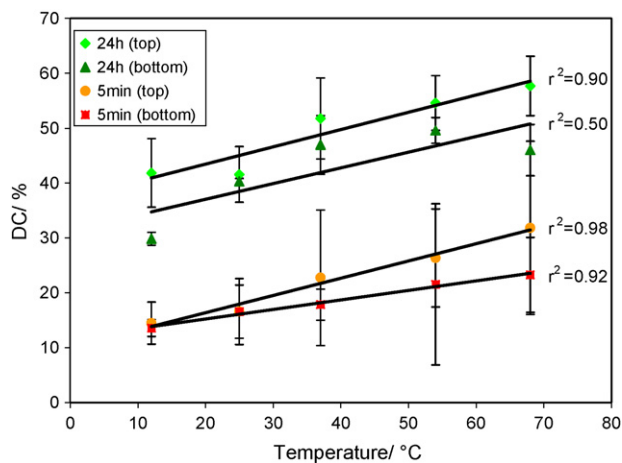


Fig. 3 – Results of % DC on top and bottom surfaces of the pre-heated resin composites.

after placement in the cavity), all materials approached the 37 °C equilibrium at the bottom of the cavity. A dentin temperature increase of 5.0 °C (at 10 °C) to 6.8 °C (at 68 °C) was measured due to light-curing, reaching maxima at the end of the irradiation period. A suppressed and delayed dentin temperature profile was observed at a 2 mm distance from the cavity floor. Only a 0.5 °C temperature increase could be assigned to composite pre-heating at 68 °C and further 2.1 °C due to light-curing, reaching the maximum 4 s after the end of the irradiation period.

3.2. Degree of conversion (DC)

Regarding the different pre-heating temperatures, highest monomer conversion was observed at elevated temperatures for both storage periods, as shown in Fig. 3. At the top (directly irradiated) surface a maximum monomer conversion of 31.8% after 5 min (68 °C) was measured. At bottom (distance of 2.0 mm) surfaces, a far reduced monomer conversion of 23.3% was observed (5 min/68 °C). After 24 h dark and dry storage at 37 °C, the resin composite produced significantly greater monomer conversion for either measurement site. A maximum of 57.7% (68 °C) was detected at the top surface, and 49.6% (54 °C) at the bottom surface. Statistically significant linear correlations between % DC and the applied pre-heating temperatures of $r^2 = 0.98$ (top, 5 min), $r^2 = 0.92$ (bottom, 5 min), and $r^2 = 0.90$ (top, 24 h) were obtained, but not for the 24 h bottom measurement ($r^2 = 0.50$). In general, improved conversion was found after 24 h storage compared to 5 min and on the directly irradiated surfaces compared to the bottom sites.

Three-way ANOVA indicated no interactions between the independent variables (site, storage time, pre-heating temperature). All combinations could be clearly distinguished. After 5 min, the measurements at top and bottom surfaces produced statistically homogenous % DC, regardless of the pre-heating temperature. Among the 24 h storage groups, the highest % DC (57.7%) was measured after pre-heating of 68 °C at the top site. Following the 24 h storage, the % DC at 39, 54, and 68 °C showed statistically homogenous results for both top and bottom surfaces. After 24 h, the % DC at bottom sur-

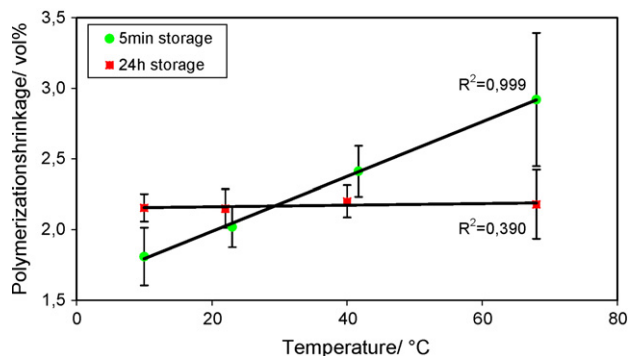


Fig. 4 – Results of volumetric polymerization shrinkage of the pre-heated composites.

faces was significantly lower (29.9%) at the 10 °C pre-heating temperature group.

3.3. Polymerization shrinkage

Fig. 4 shows the volumetric polymerization shrinkage of the resin composite at different pre-heating temperatures after 5 min and 24 h storage. The lowest shrinkage of 1.81 vol.% was measured for the 10 °C pre-cooled composite after 5 min. The greatest values of 2.85 vol.% were obtained from the 68 °C specimens after 5 min. The immediate measurements showed a linear correlation of PS as a function of pre-heating temperature ($r^2 = 0.999$). After 24 h wet storage at 37 °C, the material exhibited a homogenous dimensional behavior, with PS values ranging between 2.15 and 2.20 vol.% ($p > 0.05$).

4. Discussion

The research hypothesis has to be partly rejected, since regardless of the storage interval, no significant increase in degree of conversion has been measured from composite pre-heating at 68 °C compared to 54 and 39 °C.

Literature values for PS of hybrid resin composites range between 2 and 3 vol.% [20]. PS at different pre-heating temperatures exhibited a significant discrepancy between 5 min and 24 h measurements. Only the value measured after 5 min at room temperature (23 °C) statistically corresponds to the dimensions after 24 h. Depending on the temperature after 5 min, the resin composite shows shrinkage from elevated temperatures or expansion from reduced temperatures towards the physiological level within the first 24 h. One possible reason is the thermal expansion behavior of methacrylate-based resin composites during the 24 h storage at 37 °C. Measurements of the coefficient of thermal expansion (CTE) have shown a high expansion on heating of approx. $65 \times 10^{-6} 1/K$ [16]. Volumetric contraction (e.g. due to material cooling from 68 to 37 °C, increases the density of the polymerized specimen and thus decreases volumetric shrinkage from 2.92 to 2.17 vol.%.

In literature, several methods have been described for measuring the volumetric shrinkage, including the bonded disc method, mercury dilatometer, linometer or employing the Archimedes' principles of buoyancy [21–23]. The latter has

demonstrated values in agreement with the present study for the same resin composite [23]. A low PS is essential for development of low polymerization stresses and for a proper marginal sealing to cavity walls. Kakaboura et al. [24] correlated the volumetric shrinkage to marginal adaptation in class I cavities. They found an increased interfacial gap volume at bottom sites of non-bonded restorations due to different extent of shrinkage. Increased PS, as found in heated composites, induces higher polymerization stresses and therefore may affect the clinical performance of bonded restorations [17]. It has been shown that primary factors influencing PS are related to monomer conversion [4,17]. This is supported by the results under investigation. After 5 min storage, highest % DC (26.4 and 31.8%) along with highest PS (2.47 and 2.92 vol.%) were measured following pre-heating of 54 and 68 °C, respectively. Post-curing after 24 h led to a substantially increased monomer conversion of 54.6% (at 54 °C) to 57.7% (at 68 °C). Post-curing is frequently reported to take place due to a delay of autodeceleration at elevated temperatures and diffusion controlled reactions in the polymerized state [25].

Monomer conversion has been extensively measured using FTIR technique. The measurement of bottom cure profile using the FTIR technique was reported to produce highly reliable results [26]. Values between 55 and 75% DC have been reported for dimethacrylate-based resin composites [27]. The bottom % DC follows the top surface behavior in terms of constantly reduced monomer conversion in a depth of 2 mm. This is in common with literature findings [8]. Emami and Söderholm [28] measured similar surface and bottom % DC until a distance of 2 mm to the irradiation surface. They observed a decreased % DC in a depth of 4 mm. Manifold factors like filler type and size, color shade, and light energy density are influencing the depth of cure [29]. Most manufacturers recommend a maximum curing depth of 1.5–2 mm and the application of layering technique to succeed a rather uniform conversion and to reduce the PS. Pre-heating of composites prior to photo-polymerization has been shown to produce improved immediate monomer conversion, compared with physiological conditions [8]. The results of the present study confirm the dependency of % DC on pre-heating temperatures. However, after 24 h the advantageous effect of increased % DC is less distinctive, as shown in Fig. 3. It is well documented that shrinkage and monomer conversion are closely related factors regarding the photo-polymerization process of dental materials [30]. Improved % DC is generally associated with a higher PS and a linear relationship has been demonstrated between shrinkage strain and % DC [4]. A comparison among the % DC and PS data measured after 24 h, points out no linear correlation. Reliable results in this context are only expected after 24 h storage due to a post-curing process [31].

By placement of pre-heated bulk composites into oral cavities, factors such as specific heat capacity and thermal diffusivity of the restorative and underlying dentin have to be considered [32]. It has been reported that thermal insulation is not of major significance comparing lining materials with human dentin [33]. Patients are reported to feel pain at temperatures approaching 45 °C, induced by a 11.2 °C temperature rise at the dentinopulpal junction [34]. In vivo temperature maxima have been established during oral function [35]. Extreme values on tooth surfaces from 0 to 70 °C have been

measured after external stimuli (i.e. cold/hot drinks, food, etc.). However, the latter are short in duration and are attenuated by the surrounding soft tissues to a level that does not harm the pulp [33]. The dentin temperature profiles recorded in the present study exhibited only a small effect of pre-heating composites on intra-cavity temperature development. A maximum increase of 1.2 °C (at 68 °C) or respectively a maximum decrease of 2.2 °C (at 12 °C) has been observed prior to light exposure.

However, a major temperature effect is related to the exothermic reaction during photo-polymerization as well as to the temperature rise produced by the curing unit that caused a maximum temperature increase of 4.2 °C (at 68 °C) [36,37]. Measurement through a 2 mm wet dentin disk limited temperature rise only to 1.2 °C, apparently due to the enhanced thermal insulating properties of thick dentin. These findings here are in accordance with recently published data. Daronch et al. [10] measured in vitro intrapulpal temperature rise after placement of pre-heated composites. The authors measured a temperature rise of 0.8 °C through 1 mm wet dentin after placement of a 60 °C pre-heated composite and additional 5 °C temperature rise due to the light-curing process. They concluded that temperature drops rapidly upon complete removal from the pre-heating device, decreasing the temperature at placement to 36 °C. A less rapid temperature drop is expected in the present study, since the material has been used in syringes that have greater heat capacity [7].

From the results of the present study, it can be recommended to use resin composites at room or physiological temperatures, but not at reduced temperatures (e.g. directly from the refrigerator). Pre-heating of resin composites can be beneficial from a clinical standpoint, since a reduced viscosity at elevated temperatures improves handling and marginal adaptation of the unset material paste. However, this pre-treatment may affect composite packability and increase stickiness to the instruments. It can be further questioned, if the advantageous effect of better marginal adaptation of the unset material is clinically relevant for the marginal quality of the set material, since temperature rapidly drops to the physiological level upon removal from the pre-heating device.

REFERENCES

- [1] Geurtsen W. Biocompatibility of resin-modified filling materials. *Crit Rev Oral Biol Med* 2000;11:333-55.
- [2] Manhart J, Kunzelmann KH, Chen HY, Hickel R. Mechanical properties of new composite restorative materials. *J Biomed Mater Res (Appl Biomater)* 2000;53:353-61.
- [3] Yoon TH, Lee YK, Lim BS, Kim CW. Degree of polymerization of resin composites by different light sources. *J Oral Rehabil* 2002;29:1165-73.
- [4] Silikas N, Eliades G, Watts DC. Light intensity effects on resin-composite degree of conversion and shrinkage strain. *Dent Mater* 2000;16:292-6.
- [5] Lohbauer U, Rahiotis C, Krämer N, Petschelt A, Eliades G. The effect of different light-curing units on fatigue behavior and degree of conversion of a resin composite. *Dent Mater* 2005;21:608-15.
- [6] Leinfelder KF, Bayne SC, Swift Jr EJ. Packable composites: overview and technical considerations. *J Esthet Dent* 1999;11:234-49.
- [7] Daronch M, Rueggeberg FA, Moss L, De Goes MF. Clinically relevant issues to preheating composites. *J Esthet Restor Dent* 2006;18:340-50.
- [8] Daronch M, Rueggeberg FA, De Goes MF. Monomer conversion of pre-heated composite. *J Dent Res* 2005;84:663-7.
- [9] Lovell LG, Newman SM, Bowman CN. The effect of light intensity, temperature, and comonomer composition on the polymerization behavior of dimethacrylate dental resins. *J Dent Res* 1999;78:1469-76.
- [10] Daronch M, Rueggeberg FA, Hall G, De Goes MF. Effect of composite temperature on in vitro intrapulpal temperature rise. *Dent Mater* 2007;23:1283-8.
- [11] Asmussen E, Peutzfeld A. Influence of pulse-delay curing on softening of polymer structures. *J Dent Res* 2001;80:1570-3.
- [12] Vaidyanathan J, Vaidyanathan TK. Interactive effects of resin composition and ambient temperature of light curing on the percentage conversion, molar heat of cure and hardness of dental composite resins. *J Mater Sci: Mater Med* 1992;3:19-27.
- [13] Cook WD. Thermal aspects of the kinetics of dimethacrylate photopolymerization. *Polymer* 1992;33:2152-61.
- [14] Daronch M, Rueggeberg FA, De Goes MF, Giudici R. Polymerization kinetics of pre-heated composite. *J Dent Res* 2006;85:38-43.
- [15] Trujillo M, Newman SM, Stansbury JW. Use of near-IR to monitor the influence of external heating on dental composite photopolymerization. *Dent Mater* 2004;20:766-77.
- [16] Sidhu SK, Carrick TE, McCabe JF. Temperature mediated coefficient of dimensional change of dental tooth-colored restorative materials. *Dent Mater* 2004;20:435-40.
- [17] Braga RR, Ballester RY, Ferracane JL. Factors involved in the development of polymerization shrinkage stress in resin-composites: a systematic review. *Dent Mater* 2005;21:962-70.
- [18] Watts DC, Issa M, Ibrahim A, Wakiaga K, Al-Samadini M, Silikas N. Edge strength of resin-composite margins. *Dent Mater* 2008;24:129-33.
- [19] Kell GS. Density, thermal expansivity, and compressibility of liquid water from 0 to 150 °C: correlations and tables for atmospheric pressure and saturation reviewed and expressed on 1968 temperature scale. *J Chem Eng Dat* 1975;20:97-105.
- [20] Weinmann W, Thalacker C, Guggenberger R. Siloranes in dental composites. *Dent Mater* 2005;21:68-74.
- [21] Kim SH, Watts DC. Polymerization shrinkage-strain kinetics of temporary crown and bridge materials. *Dent Mater* 2004;20:88-95.
- [22] De Gee AF, Feilzer AJ, Davidson CL. True linear polymerization shrinkage of unfilled resins and composites determined with a linometer. *Dent Mater* 1993;9:11-4.
- [23] Guggenberger R, Weinmann W, Kappler O, Fundingsland J, Thalacker C. Historical evolution of volumetric polymerization shrinkage of restorative composites. *J Dent Res* 2007;86(spec iss A):403.
- [24] Kakaboura A, Rahiotis C, Watts D, Silikas N, Eliades G. 3D-marginal adaptation versus setting shrinkage in light-cured microhybrid resin composites. *Dent Mater* 2007;23:272-8.
- [25] Schneider LFJ, Consani S, Ogliaeri F, Correr AB, Sobrinho LC, Sinhoreti MAC. Effect of time and polymerization cycle on the degree of conversion of a resin composite. *Oper Dent* 2006;31:489-95.
- [26] DeWald JP, Ferracane JL. A comparison of four modes of evaluating depth of cure of light-activated composites. *J Dent Res* 1987;66:727-30.

- [27] Palin WM, Fleming GJP, Burke TFJ, Marquis PM, Randall RC. Monomer conversion versus flexure strength of a novel dental composite. *J Dent* 2003;31:341–51.
- [28] Emami N, Söderholm KJM. How light irradiance and curing time affect monomer conversion in light-cured composites. *Eur J Oral Sci* 2003;111:536–42.
- [29] Peutzfeld A. Resin composites in dentistry: the monomer system. *Eur J Oral Sci* 1997;105:97–116.
- [30] Rahiotis C, Kakaboura A, Loukidis M, Vougiouklakis G. Curing efficiency of various types of light-curing units. *Eur J Oral Sci* 2004;112:89–94.
- [31] Dewaele M, Truffier-Boutry D, Devaux J, Leloup G. Volume contraction in photocured dental resins: the shrinkage–conversion relationship revisited. *Dent Mater* 2006;22:359–65.
- [32] Saitoh M, Masutani S, Saigoh M, Hirose H, Nishiyama M. Thermal properties of dental materials—cavity liner and pulp capping agent. *Dent Mater J* 2004;23:399–405.
- [33] Little PAG, Wood DJ, Bubb NL, Maskill SA, Mair LH, Youngson CC. Thermal conductivity through various restorative lining materials. *J Dent* 2005;33:585–91.
- [34] Lisanti VF, Zander HA. Thermal conductivity of dentine. *J Dent Res* 1950;29:493–7.
- [35] Barclay CW, Spence D, Laird WRE. Intra-oral temperatures during function. *J Oral Rehabil* 2005;32:886–94.
- [36] Loney RW, Price RBT. Temperature transmission of high-output light-curing units through dentin. *Oper Dent* 2001;26:516–20.
- [37] Baroudi K, Silikas N, Watts DC. In vitro pulp chamber temperature rise from irradiation and exotherm of flowable composites. *Int J Paediatr Dent*, available online DOI:10.1111/j.1365-263X.2007.00899.x.