Effect of irradiation type (LED or QTH) on photo-activated composite shrinkage strain kinetics, temperature rise, and hardness


This study compares commercially available light-emitting diode (LED) lights with a quartz tungsten halogen (QTH) unit for photo-activating resin-based composites (RBC). Shrinkage strain kinetics and temperature within the RBC were measured simultaneously using the ‘deflecting disc technique’ and a thermocouple. Surface hardness (Knoop) at the bottom of 1.5-mm thick RBC specimens was measured 24 h after irradiation to indicate degree of cure. Irradiation was performed for 40 s using either the continuous or the ramp-curing mode of a QTH and a LED light (800 mW cm\(^{-2}\) and 320 mW cm\(^{-2}\), respectively) or the continuous mode of a lower intensity LED light (160 mW cm\(^{-2}\)). For Herculite XRV and Filtek Z250 (both containing only camphoroquinone as a photo-initiator) the QTH and the stronger LED light produced similar hardness, while in the case of Definite (containing an additional photo-activator absorbing at lower wavelength) lower hardness was observed after LED irradiation. The temperature rise during polymerization and heating from radiation were lower with LED compared to QTH curing. The fastest increase of polymerization contraction was observed after QTH continuous irradiation, followed by the stronger and the weaker LED light in the continuous mode. Ramp curing decreased contraction speed even more. Shrinkage strain after 60 min was greater following QTH irradiation compared with both LED units (Herculite, Definite) or with the weaker LED light (Z250).

The most widely used light sources for photo-activating resin-based composites (RBC) are quartz tungsten halogen (QTH) lights. The radiation emitted by these incandescent lamps is band-pass filtered to a spectrum starting between 380 nm and 400 nm and ending between 500 and 520 nm (1–4). Since only a small part of the spectral range emitted by incandescent lamps is appropriate for activating the photo-initiators, the efficiency of QTH lights is low. Moreover, the spectral irradiance is lower at the blue end of the visible range and continually increases towards the red end, which unfortunately does not contribute to activation of photo-initiators. In addition, a considerable amount of heat is generated, requiring the use of cooling fans. Cooling problems limit the development of higher energy lights which might allow the reduction of irradiation times so as to save clinicians’ time. Because of the bandpass filtering described above, the spectrum emitted by QTH lights is suitable for activating the most commonly used photo-initiator, camphoroquinone (CQ), with a maximum absorption at 468 nm, as well as alternative initiators absorbing at wavelengths shorter than 450 nm. In addition to increasing irradiance, recent developments have focused on providing units featuring various irradiation protocols, such as starting irradiation at low light intensity and switching to full intensity thereafter (step-curing) or gradually increasing intensity (ramp-curing). These soft-start curing modes reduce polymerization contraction stress (5,6) and lower contraction strain (7), and are therefore expected to better preserve margin integrity and marginal seal of RBC restorations. This effect has been confirmed by a considerable number of studies (8–13) but not by all (14,15).

Argon-ion lasers emit light at distinct frequencies or at a family of distinct frequencies. Blue lasers have been used successfully for photo-activating RBC (16–18). Yet, for economical reasons, these systems have not found wide acceptance.

The spectrum emitted by plasma arc (PAC) lamps features ranges of especially high intensity. On suitable selection of the gases contained in these arc lamps, the peak intensity regions may coincide with the maximum absorption of the photo-initiators (e.g. CQ). Nevertheless, filters are used to block undesired wavelengths. The first commercially available PAC lights were filtered to a spectral range of 440 nm or 450 nm to 500 nm, which is
optimally suited for activating CQ. Consequently, these units did not appropriately activate RBC containing alternative initiators absorbing at shorter wavelengths in addition to CQ (19). Currently, PAC lights emitting a spectral range between 380 nm and 500 nm are also available. However, even these units feature the highest spectral irradiance between 450 nm and 500 nm. The high irradiance of PAC lights allows the reduction of curing times. Yet exposure durations as short as 1–3 s, as initially recommended by some manufacturers, were not sufficient for the majority of RBC brands (19, 20). Moreover, these units sell at several times the price of QTH lights. Concerns have been raised regarding radiation heating created by the high light intensity and negative side-effects of the rapid polymerization shrinkage, which may compromise the marginal seal of restorations.

Light-emitting diodes (LEDs) feature very narrow spectral ranges and are therefore highly efficient light sources. Their spectral irradiance depends on the chemical composition of semiconductors used. Red LEDs have been widely used for quite some time, but blue LEDs providing sufficient irradiance for activating RBC have become available only recently (21–24). The high efficiency of LEDs allows the development of battery-powered cordless lights and eliminates the need for cooling fans. The narrow bandwidth of emitted radiation (23) should be optimally suited for activating CQ, but alternative photo-initiators absorbing at shorter wavelengths will most likely not be sufficiently activated. Heating of the irradiated objects by LED lights is expected to be minimal. Reports on shrinkage strain kinetics produced by LED irradiation are not yet available.

The present study tested the hypothesis that two commercially available LED light sources are equivalent to a high-irradiance QTH unit for photo-activating RBC, while lowering the temperature rise during polymerization commonly associated with QTH lights. For this purpose, shrinkage strain kinetics and the temperature rise during polymerization were determined using the deflecting disc technique (25, 26) modified for simultaneous measurement of the temperature within the RBC. In addition, the degree of cure was determined indirectly by measuring surface hardness (Knoop).

Materials and methods

Resin composites

Three commercially available RBC were selected for the study to represent a range of different types of photo-activators, curing speeds, and shrinkage strains (Table 1). Hereulite XRV (Kerr Italia, Seafati (SA), Italy) has been available for a long time, is well documented in the literature and is considered representative of many other available ultrafine midway-filled (27) hybrid resin composites. Filtek Z250 (3M Dental Products, St Paul, MN, USA) stands out for its high modulus of elasticity and its fast curing characteristics. Definite (Degussa, Hanau, Germany) was selected for this study to represent the new type of materials incorporating inorganic components, namely crosslinked polysiloxanes, into the matrix. Whereas Herculite XRV and Z250 use exclusively camphoroquinone (maximum absorption at 468 nm) as a photo-initiator, Definite contains an additional photo-activator absorbing at wavelengths shorter than 450 nm.

Curing protocols

Two LED curing units of different irradiance (LED1 > LED2) were available for the study. A quartz tungsten halogen light served as a control. The QTH and one of the LED units (LED1) feature a continuous as well as a ramp-curing mode, both of which were included in the study. The names and manufacturers of the curing lights and the details regarding the curing protocols are specified in Table 2.

The spectral irradiance of the curing lights was determined using an integrating sphere (FOIS, Ocean Optics, Dunedin, FL, USA) and a fiber optic spectrometer (HR2000; Ocean Optics) equipped with a 10-μm slit and a 600 l mm$^{-1}$ 1 grating at a scan rate of at least 10 s$^{-1}$. The spectral response of the system was calibrated using a National Institute of Standards and Technology (NIST) traceable calibrated light source (LS1-CAL-INT; Ocean Optics). Spectral irradiance was determined by averaging the spectra recorded during one complete curing period using the continuous mode of each curing light. Irradiance was calculated by integration of

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Shade</th>
<th>Batch</th>
<th>Filler load (wt%)</th>
<th>Filler load (vol.%)</th>
<th>Content of photo-initiators with maximum absorption within following ranges of wavelengths $^\text{1}$</th>
</tr>
</thead>
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<tr>
<td>Herculite XRV</td>
<td>Ultrafine midway-filled</td>
<td>A2 Dentin</td>
<td>0–1132,2003–5</td>
<td>87.1$^1$</td>
<td>59$^3$</td>
<td>Yes$^2$</td>
</tr>
<tr>
<td>Filtek Z250</td>
<td>Hybrid resin composite</td>
<td>A2</td>
<td>9AK 2002–03</td>
<td>82$^1$</td>
<td>60$^1$</td>
<td>No $^2$</td>
</tr>
<tr>
<td>Definite</td>
<td>Hybrid resin composite</td>
<td>A2</td>
<td>CH217,2002-06-30</td>
<td>75$^1$</td>
<td>62$^1$</td>
<td>Yes$^2$</td>
</tr>
</tbody>
</table>

$^1$Specification of the manufacturer.

$^2$Camphoroquinone-containing.
the spectra and plotted vs. time. Throughout the study, irradiance was monitored using a handheld radiometer (Curing Radiometer; Demetron, Danbury, CT, USA).

Shrinkage strain kinetics and temperature rise

Polymerization shrinkage strain was determined using the deflecting disc technique originally described by WILLS et al. (25) and WATTS & CASH (26) (Fig. 1). Standardized volumes of RBC (approx. 65 mm³) were placed between a microscope slide and a microscope cover-slip supported by a brass ring (inner diameter 15 mm, height 1.5 mm). A pair of type K thermocouple wires (NiCr–Ni, #32.230.283; Chempur, Karlsruhe, Germany) were threaded through holes in the brass ring with the stripped and twisted portion located at the center of the RBC specimens in order to monitor the temperature within the composite. Specimens were irradiated from below through the microscope slide. Deflection of the cover-slip indicating polymerization contraction strain was recorded using an inductive displacement transducer (W1T 3-2; HBM, Darmstadt, Germany), while a photo sensor served to indicate the start of irradiation. Specimens were irradiated for a second and third time 60 min and 65 min after the first exposure for reasons explained below. All experiments were carried out in an oven maintained at 37°C. Data acquisition was performed using an AD conversion board and a PC at a sampling rate of 10 data points s⁻¹. Five minutes after the final irradiation, the height of the RBC specimen was determined by subtracting the thickness of the microscope slide (measured in triplicate next to the composite specimen using a micrometer screw (Mahr, Esslingen, Germany)) from the thickness of the specimen still attached to the slide. The absolute values for contraction strain were converted to percentages of the initial specimen height. Shrinkage strain was plotted vs. time and a linear fit was calculated at the maximum slope of the resulting curve. The slope of this straight line indicated the maximum rate of contraction and its axial section the contraction delay (Fig. 2). For graphic presentation, the curves of the individual specimens in each treatment group were averaged.

The temperature rise during the first exposure is caused both by the reaction heat of the exothermic polymerization and physically by the radiation itself. During the subsequent exposures, however, most of the polymerization was already completed and the observed temperature rise was predominantly caused by radiation heating (Fig. 3). By superposition and subtraction of these curves, the temperature rise caused by exothermic heat was calculated (28,29). Specimens not completely cured after the first exposure may have had different temperature rises, which were corrected for in the analysis.

Table 2

<table>
<thead>
<tr>
<th>Curing protocols</th>
<th>Code</th>
<th>Light curing unit</th>
<th>Serial No.</th>
<th>Setting</th>
<th>Description (duration and intensity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halogen continuous exposure</td>
<td>QTH Cont</td>
<td>Elipar Trilight¹</td>
<td>3900248</td>
<td>std</td>
<td>40 s at 800 mW cm⁻²</td>
</tr>
<tr>
<td>Halogen ramped exposure</td>
<td>QTH Ramp</td>
<td>Elipar Trilight¹</td>
<td>3900248</td>
<td>exp</td>
<td>5 s at 100 mW cm⁻²; exponential increase to 800 mW cm⁻² within 10 s, 25 s at 800 mW cm⁻²</td>
</tr>
<tr>
<td>LED Unit #1 continuous exposure</td>
<td>LED1 Cont</td>
<td>Elipar Freelight¹</td>
<td>P000024</td>
<td>std</td>
<td>Exponential increase to 320 mW cm⁻² within 10 s, 30 s at 320 mW cm⁻²</td>
</tr>
<tr>
<td>LED Unit #1 ramped exposure</td>
<td>LED1 Ramp</td>
<td>Elipar Freelight¹</td>
<td>P000024</td>
<td>exp</td>
<td>1 s at half energy, 39 s at full energy (160 mW cm⁻²)</td>
</tr>
<tr>
<td>LED Unit #2 continuous exposure</td>
<td>LED2 Cont</td>
<td>Luxomax AP 100²</td>
<td>20.023.919</td>
<td>1/39</td>
<td></td>
</tr>
</tbody>
</table>

¹3M ESPE, Seefeld, Germany.
²Akeda Dental, Lystrop, Denmark.
³Curing Radiometer (Demetron, Danbury, CT, USA).

![Fig. 1. Experimental set-up for evaluation of shrinkage kinetics using the 'deflecting disc technique' described by WILLS et al. (25) and WATTS & CASH (26), modified for simultaneous measurement of temperature within the resin composite.](image)

![Fig. 2. Analysis of polymerization contraction strain data.](image)
produce additional exothermic heat and contraction during the second exposure. Therefore, the present study used the data recorded for the third exposure for calculation of the temperature rise caused by exothermic heat. The curves of the six specimens per treatment group were averaged for graphic presentation of the temperature rise during polymerization and the temperature rises caused by radiation or by exothermic heat. The respective maximum values were determined and analysed for statistically significant differences among treatment groups.

**Hardness**

Specimens of the same volume as stated above were cured between two microscope slides using spacers of 1.6 mm. Specimens were stored dry at 37°C in the dark until testing. When resin composites are polymerized against a matrix band, the percentage of unreacted double bonds is up to twice as high at the interface with the matrix band than in the bulk of the material, even when the specimens are prepared in an argon atmosphere (30). This phenomenon can be explained by the fact that in the bulk of the material a free radical is surrounded three-dimensionally by possible reaction partners, while a radical located at the interface can find possible reaction partners only on one side of a hypothetical sphere centered on the free radical. Therefore, hardness at the surface is lower than that 80–100 μm into the bulk. To account for this interface effect, a 0.1-mm layer was removed, prior to testing, by wet grinding from the surface opposite to the side from which the specimens had been irradiated. Knoop hardness was measured 24 h after polymerization using a hardness tester (Zwick, Ulm, Germany) applying a load of 4.905 N (0.5 kp) for 30 s. Three indentations were evaluated and averaged for each specimen.

**Statistical evaluation**

For every combination of RBC and curing mode, six specimens were prepared and tested for polymerization shrinkage kinetics, temperature rise and hardness. The results were analysed by one-way ANOVA for each resin composite separately. Differences between the curing modes were evaluated using Tukey’s post hoc test at a significance level of $P < 0.05$. All calculations were performed using the computer program SPSS 10.0 (SPSS, Chicago, IL, USA).

**Results**

**Spectral irradiance**

Figure 4 displays the spectral irradiance of the different curing lights. The QTH unit covered the spectral range between 418 nm and 507 nm (width at half peak height). The LED lights featured narrow spectral ranges (LED1, 453–479 nm; LED 2, 456–481 nm) with maximum irradiances at 464.8 nm and 468.3 nm, respectively. The QTH unit demonstrated a considerably higher irradiance than the LED1 and the LED2 unit. With LED1 ramp curing, irradiance increased linearly from zero to full energy within 11 s. In contrast, for
QTH ramp curing irradiance increased very slowly during the first 8 s, rose exponentially thereafter, and reached the maximum value after 15 s. For all continuous curing modes, irradiance slightly decreased during the irradiation period.

**Temperature rise during polymerization**

Figure 5 displays the temperature rise during polymerization, during subsequent irradiation and the calculated temperature rise caused by exothermic heat. The maximum rise was observed within the first 10 s (Z250) to 15 s (Herculite XRV and Definite) of irradiation in case of the continuous, between 10 s and 15 s in case of the LED1 ramp and between 23 s and 32 s in case of the QTH ramp curing protocols. Only for QTH ramp-irradiated Z250 did the maximum temperature occur at the end of the irradiation period. The difference between the maximum temperature and the temperature at the end of the irradiation period was larger for the QTH lights compared with the QTH unit. A similar ranking was observed for the maximum temperature rise caused by exothermic reaction. Again, the maximum temperatures occurred earlier with QTH continuous irradiation than with LED1 continuous and LED2 continuous irradiation. For the LED1 ramp and QTH ramp protocols, the maxima were observed even later. For all curing protocols, the maximum temperatures were reached earlier with Z250 than with Herculite XRV and Definite. The temperature rise caused by radiation continuously increased until the end of the irradiation period and

![Fig. 5. Temperature rise during polymerization (A), temperature rise due to radiation heating (B) and temperature rise from exothermic heat (C) for the different combinations of curing modes and resin-based composites (all values relative to a baseline of 37°C; curves averaged for \(n = 6\) specimens per treatment group).](image1)

![Fig. 6. Analysis of data for temperature rise during polymerization (A: mean ± SD, \(n = 6\)), temperature rise caused by radiation (B) and by exothermic heat (C). Values in/above the columns specify the respective arithmetic mean. Brackets indicate curing protocols not significantly different (Tukey: \(P ≥ 0.05\)).](image2)
exponentially decreased afterwards. Ramp-curing delayed the heating from radiation. The QTH unit produced the highest temperature rise from radiation, followed by the LED1 and LED2 light.

The results of the analysis of the temperature data are presented in Fig. 6. The highest temperature rises were observed during QTH irradiation (15.5–18.6°C). The rises recorded for the more powerful LED light (LED1) were significantly lower (8.2–12.4°C), whereas the weaker LED light (LED2) produced the lowest values (6.2–9.5°C). No significant differences were observed between the continuous and the ramp-curing modes of the same curing unit. A similar ranking was observed for the temperature rise caused by radiation. However, the differences between the QTH light (11.0–12.9°C) and the LED lights (LED1, 2.9–3.5°C; LED2, 1.4–1.5°C) were much more pronounced. For temperature rise caused by exothermic reaction, the differences between the curing modes were much smaller. For Herculite XRV and Definite, QTH produced still higher values than LED1 and LED2. For Z250, no significant differences were observed between QTH and LED1 when continuous or ramp curing were considered separately.

Polymerization shrinkage strain kinetics
The course of polymerization shrinkage strain in the different treatment groups is displayed in Fig. 7. The fastest shrinkage strain increase was observed with QTH continuous, followed by LED1 continuous and LED2 continuous irradiation. A delayed start of contraction was obvious for the ramp curing modes. At the end of the irradiation period (i.e. after 40 s), the curves of the QTH groups showed a sharp bend upwards, indicating a sudden acceleration of contraction; similar phenomena were not seen in the case of the LED lights. Definite exhibited less shrinkage strain with LED than with QTH light irradiation. Contraction strain started earlier and proceeded faster with Z250 than with Herculite XRV and (with the exception of LED curing) Definite.

The analysis of shrinkage strain data is presented in Fig. 8. The fastest contraction strain was observed for QTH continuous irradiation, followed by LED1
Continuous and LED2 continuous. The ramp irradiation modes resulted in slower progression of shrinkage than the corresponding continuous modes. The longest contraction delay was found for QTH ramp, followed by LED1 ramp and LED2 continuous. In contrast, QTH continuous and LED1 continuous featured only short contraction delays. The QTH irradiation produced more shrinkage than LED curing for Herculite XRV and Definite. The ramp modes did not result in less shrinkage than the corresponding continuous protocols.

**Hardness**

Hardness measurements are presented in Fig. 9. The lowest hardness was observed for all materials following LED2 continuous irradiation. For Z250, similar hardness values were produced by the remaining curing protocols. In the case of Herculite, QTH continuous irradiation resulted in greater hardness than with QTH ramp or LED1 curing. For Definite, QTH irradiation was superior to LED1 curing.

**Discussion**

The data presented above partly confirmed the hypothesis of the study. The stronger of the two LED units proved more or less equivalent to a QTH light for activating RBCs containing exclusively CQ as a photo-initiator. The temperature rise during polymerization was smaller with the LED units than with the QTH light.

Hardness has been shown to be a good indicator of conversion of double bonds (31,32) and was therefore used as an indirect measurement of degree of cure in the present study. Although irradiance of the QTH light and the stronger LED unit (LED1) differed by more than a factor of two when evaluated using a hand-held radiometer, the resulting hardness values were equivalent in the case of Z250 and only slightly different in the case of Herculite XRV. This finding can be explained by the fact that the higher output of the QTH light includes spectral ranges that do not contribute to activation of CQ. For comparison of curing lights markedly differing in their respective spectral irradiance, the results of simple radiometers are misleading. The same holds true for the results presented in Fig. 4B, because here the spectral irradiance was integrated over the complete spectrum of wavelengths, producing much higher results for the broadband QTH unit compared with the narrow-banded LED lights, thus overestimating the superiority of the QTH unit. In this situation, weighting the spectral irradiance for the absorption characteristics of the photoinitiator(s) may provide more meaningful results.

In the case of Definite, the additional photo-initiator was not appropriately activated by the LED lights, which explains their inferior performance for this particular RBC. Similar data have been reported for plasma arc-irradiated Definite (19). Photo-initiators absorbing at wavelengths shorter than 450 nm (e.g. Phenyl-Propane-Dione, Irgacure 640), have been used in some all-in-one adhesives (e.g. Prompt-L-Pop, 3M ESPE, Germany; Excite, Vivadent, Leichtenstein) and in light and transparent shades of RBC (e.g. Tetric Ceram Bleach; Vivadent). In the first case, the manufacturers have already changed the initiating system to accommodate narrow-range curing lights. For the second material type, such a modification may be more difficult to accomplish, since replacing the below-450 nm absorbing photo-activators by camphoroquinone will produce a yellow discoloration of these materials.

The differences between the two LED units can be explained by their different irradiance. For the lower intensity unit (LED2), longer irradiation periods may be required to produce equivalent hardness. Since double-bond conversion correlates with the product of irradiation period and intensity, i.e. the total energy applied (33,34), the required periods may be twice as long.

For QTH irradiation, the maximum temperature rise during polymerization ranged between 15.5°C and 18.6°C relative to a baseline of 37°C and therefore may be regarded as critical. The stronger LED unit produced maximum temperatures of 8.2–12.1°C and the weaker one produced maximum temperatures of 6.2–8.9°C above the baseline. Comparative literature values vary between as low as 2.4–7.1°C at the bottom of 2 mm-thick samples (29) and as high as 21.4°C at the bottom (28), and 22.0°C in the center (35) and 29.2°C at the surface (36) of RBC specimens.

It may be speculated however, that the present experimental setup tends to overestimate the thermal load during polymerization, for following reasons: thermal conductivity of the setup is low, and resin composite is in contact with the microscope slide at the bottom and the cover slip at the top. Owing to their thicknesses of only 1 mm and 0.14 mm, respectively, they have only a small thermal capacity and low conductivity, favoring larger temperature rises in the resin composite. In contrast, in the clinical situation, more restoration surface area is in contact with the surrounding cavity walls, thus facilitating heat dissipation. Dentine has a low thermal conductivity and thermally protects the pulp tissue. Here, a temperature rise of 5.5°C has been reported to damage the pulp (37,38). Plasma arc-irradiation for 10 s
caused a temperature rise in the pulp chamber of 7.8°C relative to a baseline of 37°C, whereas 6.9°C or less were recorded for QTH irradiation (39). Similar temperatures should be expected for the QTH curing protocols of the present study, with considerably lower values for LED irradiation. Finally, baseline temperatures in the clinical situation are lower than 37°C: the temperature in the oral cavity was found to be 27.7°C without placement of rubber dam and 25.1°C with placement (40). The temperature of cavity surfaces may not be much beyond these values, at least if local anesthesia is used. Resin composite pastes are used at room temperature or are even stored refrigerated to facilitate clinical handling. For these reasons, maximum temperatures during polymerization should be lower in the clinical situation than observed in the present experimental setup; however, further studies are required to confirm this hypothesis.

Although an advantage of the LED units was clearly demonstrated, the data also show that polymerization is far from isothermal even following LED irradiation. If an RBC is adequately activated, the exothermic heat is created irrespective of the type of curing unit. When radiation heating is low, as was demonstrated for the LED lights, exothermic heat is the major contribution to temperature rise during polymerization, and a greater temperature reduction even before the end of irradiation is observed than for QTH lights, where temperature is kept high by radiation heat. The lower temperature rise during polymerization and the lower rise caused by exothermic heat observed for LED-irradiated Definite cannot be regarded as an advantage, but has to be attributed to the incomplete activation of this material by the LED lights, which resulted in lower hardness values as described above.

The course of contraction strain, especially in the QTH-irradiated groups, is explained by the simultaneous occurrence of contraction from polymerization and thermal expansion or contraction from concurrent temperature changes. The temperature rise and gradual decrease during light exposure is accompanied by thermal expansion, which partly counteracts polymerization contraction. The sudden drop in temperature observed after the end of exposure produces thermal contraction which now adds to the polymerization contraction, producing the sharp upward bend of the strain curves seen in Fig. 7. Since the LED lights produced much smaller temperature changes after the end of exposure, no corresponding effects were seen in the respective shrinkage strain curves. Similar effects were also observed for polymerization contraction stress (41). Contraction strain curves recorded using 3 mm thick lower glass plates instead of the 1 mm thick microscope slides of the present study failed to reveal temperature-related effects (42). On one hand, the greater distance between the curing tip and the resin composite may have reduced radiation heating, and on the other hand, the higher thermal capacity of the thicker glass plate may have facilitated heat dissipation from the resin composite and thus have reduced thermal effects.

The delayed start and slower progression of polymerization contraction strain observed for the ramp irradiation protocols was expected on the basis of the low initial irradiance provided by these protocols. These techniques are intended to allow more time for flow to occur within the material, which may compensate for polymerization contraction, reduce contraction stress and improve the marginal seal of restorations (43). In the continuous irradiation mode, the higher intensity LED unit produced a slower contraction rate compared with the QTH light. It may be speculated that the radiation heat produced by the QTH light results in an additional acceleration of the polymerization reaction and consequently produces a faster increase of contraction strain. The comparatively low contraction rates produced by the weak LED unit are explained by its low irradiance and at the same time result in inferior hardness, indicating less than perfect cure. For shrinkage strain after 1 h, the ranking of the curing modes more or less reflected that observed for hardness, underlining the close relationship between these two parameters (44). The earlier start and faster increase of contraction strain observed for Z250 compared with Definite and Herculite XRV probably indicates a very high efficiency of the photo-activation system of this material. However, the concentrations of photo-activators contained in the different materials are not specified by the manufacturers. The earlier occurrence of maximum temperature during polymerization and of highest temperature caused by exothermic reaction observed for Z250 may be explained along the same lines.

References
7. **Sakaguchi RL, Berg HX. Reduced light energy density decreases post-gel contraction while maintaining degree of conversion in composites. J Dent 1998; 26: 695–700.**