Original Article / Özgün Araştırma

Evaluation of the Effect of Different Curing Units and Exposure Times on Pulp Chamber Temperature Using Simulated Pulpal Microcirculation

Yapay Pulpal Mikrosirkülasyonu Kullanılarak Farklı Işınlama Üniteleri ve Işınlama Sürelerinin Pulpa Odası Sıcaklığına Etkisinin Değerlendirilmesi

İhsan Furkan Ertuğrul[1], Başak Yazkan[2]

[1]Pamukkale University Faculty of Dentisry, Department of Endodontics, Denizli, Turkey
[2]Pamukkale University Faculty of Dentistry, Department of Conservative Dentistry, Denizli, Turkey

Keywords
Curing units, exposure time, pulpal temperature elevation

Anahtar Kelimeler
Işınlama cihazları, ışınlama zamanı, pulpal ısı yükselmesi

Received/Geliş Tarihi : 08.11.2018
Accepted/Kabul Tarihi : 07.02.2019

doi:10.4274/meandros.galenos.2019.43255

Address for Correspondence/Yazışma Adresi:
İhsan Furkan Ertuğrul MD,
Pamukkale University Faculty of Dentisry,
Department of Endodontics, Denizli, Turkey
Phone : +90 536 517 46 77
E-mail : furkanertugrul@gmail.com
ORCID ID: orcid.org/0000-0001-7583-6679

Abstract

Objective: To compare the elevations in physiological pulp chamber temperature and blood microcirculation during light curing using four different light sources at two different exposure times.

Materials and Methods: The study was performed on eighty Class-V cavities divided into eight groups of ten experiments each, according to the curing unit and exposure time. Short-term curing was performed in four groups: quartz-tungsten-halogen (QTH)-20 seconds (s) (XL3000, 3M ESPE, St. Paul, MN, USA); Woodpecker (WP)-15s (Lux V Light Cure Unit, WP, Apexion Dental Products); KR-10s (Demi Plus Dental Curing Light, Kerr Dental) and VL-3s (VALO light-emitting diode Curing Light Xtra Power mode, Ultradent Products, South Jordan, UT, USA). The same units were used for long-term curing at double the exposure time (i.e., QHT-40s, WP-30s, KR-20s, VL-3+3s). Composite material (Filtek Ultimate, 3M/ESPE) was placed into the cavities, followed by light curing performed at a distance of 1 mm. Temperature changes in the pulp chamber were recorded. The Kruskal-Wallis test, followed by Mann-Whitney U multiple comparisons test, were used for statistical analyses, with $p<0.001$ considered to be statistically significant.

Results: There were no significant differences among the curing units at the same exposure times. However, increases in pulp chamber temperatures varied significantly depending on the curing time ($p<0.001$). All the curing units induced significantly higher intrapulpal temperature changes at long-term curing times, except the WP groups ($p<0.001$). WP-30s, KR-20s and VL-3+3s exhibited critical temperature increases >5.5 °C.

Conclusion: Longer curing times led to critical temperature increases in the pulp chamber. Shorter curing times can protect the pulp tissue against damage caused by temperature elevations above a certain threshold.

Öz

Amaç: İki farklı ışınlama süresinde dört farklı ışık kaynağı kullanılarak ışıkla sertleştirme sırasında fizyolojik kan mikrosirkülasyonu ile birlikte pulpa odası sıcaklık artışlarını karşılaştırmak.

Gereç ve Yöntemler: Çalışma, farlı ışık kaynakları ve farklı ışınlama süresine göre, her biri 10 deneyden oluşan sekiz grupla seksen Sınıf-V kavite üzerinde gerçekleştirilmiştir. Kısa süreli kürleme dört grupta gerçekleştirildi: kuvars-tungsten-halojen (QTH) 20 saniye (XL3000, 3M ESPE, St. Paul, MN, ABD); Woodpecker (WP) -15s (Lux V Işık Tedavi Ünitesi, WP, Apexion Dental Ürünleri); KR-10s (Demi Plus Dental Kür Işık, Kerr Dental); ve VL-3s (VALO ışık yayan diyot Kür Işık Xtra Güç modu, Ultradent Ürünler, South Jordan, UT, ABD). Aynı birimler, pozlama süresinin iki katı uzun süreli ışınlama için kullanılmıştır (yani, QHT-40s, WP-30s, KR-20s, VL-3+3s). Kompozit malzeme (Filtek Ultimate, 3M/ESPE) boşluklara yerleştirildi, ardından 1 mm mesafede ışıkla sertleştirme yapıldı. Pulpa odasındaki sıcaklık değişimleri kaydedildi. Kruskal-Wallis testi, ardından Mann-Whitney U çoklu karşılaştırma testi uygulanmış, istatistiksel analizlerde p<0,001 istatistiksel olarak anlamlı bulunmuştur.
Bulgular: Aynı ışınlama süreleri içerisinde ışınlama cihazları arasında önemli bir farklılık yoktu. Bununla birlikte, pulpa odası sıcaklıklarındaki artışlar, ışınlama süresine bağlı olarak önemli ölçüde değişmiştir (p<0,001). Tüm sertleştirme üniteleri, WP grupları hariç, uzun süreli ışınlama sürelerinde, önemli ölçüde daha yüksek sıcaklık değişikliklerine neden olmuştur (p<0,001). WP-30s, KR-20s ve VL-3+3s, > 5,5 °C kritik sıcaklık artışları sergiledi.
Sonuç: Daha uzun ışınlama süreleri, pulpa odasındaki kritik sıcaklık artışlarına yol açmıştır. Daha kısa ışınlama süreleri, pulpayı belirli bir eşiğin üzerindeki sıcaklık yükselmelerinin neden olduğu hasara karşı koruyabilir.

Introduction

The detrimental effects of increased temperature in pulp tissue during restorative treatment(s) have been a concern in dentistry for decades. The classical animal study by Zach and Cohen (1) demonstrated a threshold temperature for irreversible pulpal damage to a healthy tooth when external heat is applied. An intra-pulpal temperature increase of 5.5 °C led to necrosis in 15% of the tested pulps; an increase of 11 °C induced 60% damage; and an increase of 16 °C resulted in irreversible tissue damage to 100% of the pulps tested (1). The major factors leading to pulp tissue damage include: protoplasm coagulation; vascular injury in the tissue; and expansion of the lymph fluid in the dentin tubules (2). The photopolymerization process can also cause a significant increase in temperature. In previous *in vitro* and *in vivo* experiments, temperature increases in the pulp chamber were found to be as high as 20 °C depending on the method of tooth preparation, photoactivation, and the various materials used (3-7). In some earlier *in vitro* studies, it was also found that the photopolymerization of composite resin increased the temperature in the pulp chamber by only a few degrees due to the heat insulation of the hard tissue within the tooth (8,9). Temperature increases in the pulp chamber depend on the type of light source, the output power density, exposure time to the light, the distance between the tooth and the fiber optic tip, the composite color tone, the thickness of the composite material, and the remaining dentin thickness (3-5,10,11). The increase in temperature in the pulp chamber during curing represents the sum of light energy from the curing unit and the heat from the exothermic reaction during polymerization of the composite resin (12,13).

There are many factors that affect heat build-up in the dentin pulp complex, including the intensity and duration of heat applied to the tooth, the movement of the lymph fluid in the dentin tubules, pulpal blood microcirculation, and blood flow changes in the pulp depending on the nervous system of the pulp (14). Pulpal microcirculation flow is reported to be approximately 20-60 mL/per minumum (min) per 100 g of tissue in healthy teeth (15,16). The pulpal microcirculation is known to be the primary system that regulates heat distribution inside the pulp tissue and, thus, partially absorbs external thermal heat (14-17).

The primary objective of the present study was to determine the extent to which the total heat increase due to light curing and polymerization varies with the physiological heat of the pulp chamber at 37 °C and simulated pulpal microcirculation for different curing units and exposure times.

Materials and Methods

This study was approved by the Pamukkale University Ethics Committee of the Faculty of Medicine (approval number: 06, date: 20.04.2017). Before the tooth extraction, consent forms stating that the extracted teeth can be used in scientific research were signed by the patients.

Sample Preparation

The sample size was determined at a 95% confidence interval and a significance level of 0.001

(effect size =1.37), according to the study by Kodonas et al. (18) eighty extracted-human mandibular premolar tooth was used in the study. The specimens were stored in 0.1% thymol solution until beginning of the experments. The study was performed with 8 groups of 10 experiments each.

A standardized cavity (3×4×2 mm^3) with a Class-V preparation was used with a pulpal wall thickness of 1 mm. Pulpal dentin wall thickness was confirmed using radiography. The roots were sectioned using a water-cooled carborundum disk approximately 1 mm below the cemento-enamel junction upright to the long axis of the tooth. The coronal pulpal tissues were cleaned using an excavator (EXC17, Osung, USA), and the pulp chamber was irrigated with distilled water and gently dried with air. Access to the pulpal chamber was prepared, as needed, via the proximal surface of the sample to enable insertion of a 0.4 mm diameter thermocouple wire (Figures 1, 2). The intrapulpal temperature changes during the curing of the composite resin were determined with a device that simulated pulpal blood microcirculation (12,17,19). A K-type thermocouple (TT-K-30-SLE; Omega Engineering Inc. Stanford, CT, USA) was inserted into the pulp chamber until contact with the axial wall and sealed with thermal grease (ZM-STG2; Zalman Tech Co. Ltd. Dongan-gu, South Korea). The position of the thermocouple point was confirmed radiographically from two directions. The access hole of the thermocouple wire was filled with light-curing glass-ionomer cement (Ionoseal, VOCO, Cuxhaven, Germany) to avoid leakage from the system. The thermocouple cable was connected to a data logger (DT-3891G; CEM, Shenzhen, PRC), which was connected to a personal computer to monitor temperatures changes.

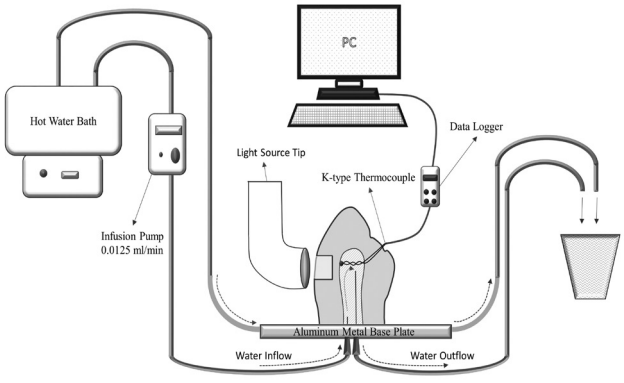

Figure 1. Schematic drawing of the mandibular premolar tooth and Class-V cavity with experimental microcirculation apparatus

Pulpal Microcirculation Simulation Model

The specimen was mounted on an experimental device made specifically for this study, which simulated pulpal blood microcirculation and regulated the temperature of the tooth to within physiological limits (37 °C ±1 °C). A standard infusion set (24.08000; Beybi Medical, İstanbul, TR) was attached to a digital water bath (WB-11; Daihan, Wonju, South Korea) holding distilled water. Two 25-gauge needles (8696569000777, Hayat Medical Co., İstanbul, Turkey) were placed to provide intrachamber microcirculation through the hole of a temperature-controlled aluminum base plate (TCAP), and used as an inflow/outflow pathway for the distilled water. Needles were attached to the drilled hole of the TCAP using cyanoacrylate adhesive. The specimens were fixed using a light-cured glass ionomer liner cement (Ionoseal; VOCO, Cuxhaven, Germany) on the TCAP in such a way that the needles lined-up with the inside of the pulp chamber. The flow rate of the distilled water was set at 0.0125 mL/min using an infusion pump set (IP12A; Biocare, Shenzhen, China), which was attached to the system (Figure 1). To provide physiological temperature in the pulp chamber, a 4 mm diameter, spiral-shape copper tube was attached under the TCAP using thermal grease and connected to a standard infusion set in a water bath. Hot water

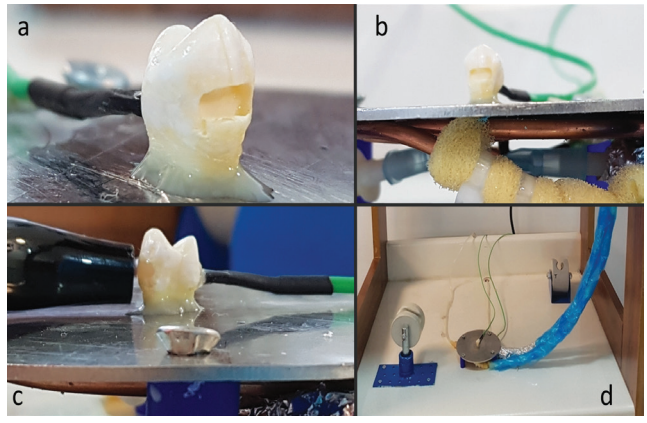

Figure 2. a: Experimental tooth Class-V cavity, b: bottom view of the "TCAP", c: the position of the tip of the irradiation device, d: top view of the test setup

TCAP: Temperature-controlled aluminum base plate

flowed from inside the copper tube to regulate physiological temperature to the TCAP (Figure 3).

Following the application of bonding agent (3M Scotchbond Multipurpose Plus, MN, USA) the cavities were restored with sufficient composite material (Filtek Ultimate, 3M/ESPE, Minneapolis, MN, USA) then light cured. Intrachamber temperature elevations were simulated by applying the various curing units with different time settings to the buccal direction of the Class-V cavity. The tips of the light sources were positioned 1 mm from the tooth. The curing units included a conventional halogen lamp and three high-intensity light-emitting diode (LED) lamps. Two different exposure times for each curing unit were tested in accordance with manufacturer's instructions. Four different curing units, their specifications, and time sets are listed in Table 1. The output power of the light-curing units were measured using a digital radiometer (Cure Rite; Caulk/Dentsply, Milford, DE, USA).

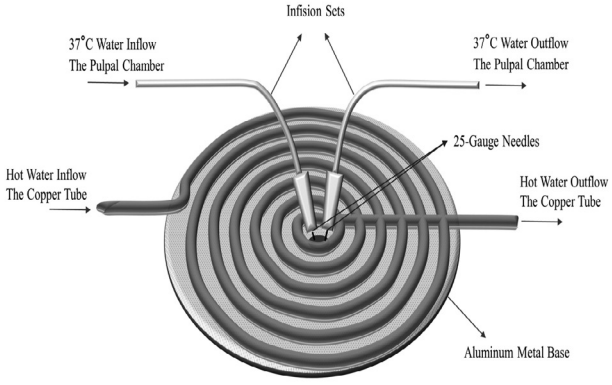

Figure 3. Bottom view of the temperature-controlled aluminum base plate, which is part of the experimental apparatus to regulate the tooth physiological temperature

Statistical Analysis

The changes between initial and maximum temperature in the pulp chamber axial wall (Δt) were recorded during the experiment, and the effect of light curing on temperature change was examined. The median changes in temperature from the initial physiological baseline are summarized in Table 1.

The Shapiro-Wilk omnibus normality test revealed that the data were not normally distributed. The Kruskal-Wallis test, followed by Mann-Whitney U multiple comparisons test, was used for statistical analyses (SPSS version 23.0, IBM Corporation, Armonk, NY, USA); $p<0.001$ was considered to be statistically significant.

Results

The median and interquartile ranges of maximum temperature increases according to the different light-curing sources and curing time sets are presented in

Table 1. Light-curing units used in the study and the median and interquartile ranges of temperature increases obtained from the test groups and intergroup comparisions

Groups	Light-curing units	Light type	Output of light tip (mW/cm²)	Curing time (s)	Temperature increase (Δt) (Median and IQR)
QTH-20 s	XL3000 (3M ESPE, St. Paul, MN, USA)	QTH	640	20	3.75 (3.3-4.5)[ab]
WP-15 s	Lux V Light Cure Unit (Woodpecker, Guangxi, China)	LED	1.000	15	4.45 (4-5)[ac]
KR-10 s	Demi™ Plus Dental Curing Light (Kerr Dental, USA)	LED	1.200	10	3.9 (3.7-4.3)[a]
VL- 3 s	VALO LED Curing Light Xtra Power mode (Ultradent, South Jordan, Utah)	LED	3.200	3	4 (3.8-4.9)[ae]
QTH-40 s	XL3000 (3M ESPE, St. Paul, MN, USA)	QTH	640	40	5.4 (5.1-5.9)[cde]
WP-30 s	Lux V Light Cure Unit (Woodpecker, Guangxi, China)	LED	1.000	30	5.85 (5.4-6.4)[d]
KR-20 s	Demi™ Plus Dental Curing Light (Kerr Dental, USA)	LED	1.200	20	5.85 (5.2-6)[cd]
VL-3/3 s	VALO LED Curing Light Xtra Power mode (Ultradent, South Jordan, Utah)	LED	3.200	3/3	5.85 (4.6-6.2)[cd]

*There are no significant differences between temperature increases with the same superscript letter

(Kruskal-Wallis test, Post-hoc Bonferroni test, $p<0.001$), IQR: Interquartile Ranges, mW/cm²: Millwatt/square centimeter, s: Second, Δt: Temperature changes, LED: Light-emitting diode, QTH: Quartz-tungsten-halogen, The same superscript letters are demonstrated no significant differences ($p<0.05$)

Table 1. There was no significant difference among all light curing units in both short- and long-term curing applications. However, pulp chamber temperature increases varied significantly depending on curing time [p<0.001 (Kruskal-Wallis test)]. All tested light-curing sources induced significantly higher intrachamber temperature changes in the long-term curing times, except for the WP group [p<0.001 (Bonferroni post-hoc test)].

The WP-30s, KR-20s and -3+3s groups demonstrated statistically significant critical temperature increases (i.e., >5.5 °C) (Table 2). The maximum temperature increase was observed on completion of light exposure (Figure 4).

Discussion

In deep restorations, the heat generated by light curing of the composite and the effect of this heat on the pulp are particularly important. Whitworth et al. (20) found that pulp damage was increased during deep restorations. When amalgam and composite deep restorations were compared, the incidence of pulp damage in the composite restorations was higher. Results of our model suggest that temperature increases in the pulp chamber and microcirculation during the curing of deep restorations varied with different curing units and at different times. It was clear that the increase in pulpal temperature varied according to the situation, and negatively affected the health of the pulp tissue; however, it was not clear at which temperature increment the pulp tissue was affected in the negative direction. Zach and Cohen (1) found that a temperature increase of 5.5 °C in the pulp tissue of rhesus monkey teeth caused necrosis in 15% of the pulp tissues. This was consistent with results reported by Pohto and Scheinin (19), and suggests that the irreversible damage of pulp tissue begins at 42-44 °C. The previous study by Zach and Cohen (1) demonstrated that pulp chamber temperature increased in a linear fashion because of the heat source used. However, in the present study, temperature increases due to the sum of the energy resulting from the light energy and the composite polymerization energy during light curing did not exhibit a linear progression (Figure 3). In a different study on human teeth reported that short-term temperature increases that were increased up to 14.7 °C did not cause degenerative changes in pulp tissue (21), while in another study, it was found that a temperature increase of 11-20 °C caused damage to the tissue (22). Safe temperature criteria for pulp tissue may be developed more accurately with the use of cultured cells and varying curing times (23,24). In this context, it is necessary to develop more detailed safety criteria based on temperature.

In vitro studies depend on many factors, such as temperature increase, the heat/light source, application time, thickness of the dental tissue, and microcirculation in the pulp chamber (12,17,18). In a previous study, the coronal pulp chamber volume of the mandibular premolar teeth was estimated to be 0.025 mL, and a serum infusion pump was set to a flow rate 0.0125 mL/min to simulate microcirculation in the pulp chamber (25). In several previous studies, the microcirculation did not take into account the contribution of regulating temperature in the pulp chamber (26-28). Many *in vitro* studies have been

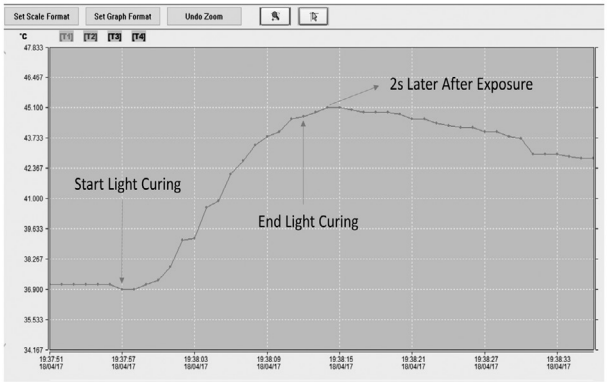

Figure 4. A graph which is showing the temperature increase during and after the 15 seconds exposure period

Table 2. Distributions of experiments below and above the critical temperature of 5.5 °C

Groups	Below 5.5 °C (n)	Above 5.5 °C (n)
QTH-20 s	10 (100%)	0 (0%)
WP-15 s	10 (100%)	0 (0%)
KR-10 s	10 (100%)	0 (0%)
VL-3 s	10 (100%)	0 (0%)
QTH-40 s	5 (50%)	5 (50%)
WP-30 s	1 (10%)	9 (90%)
KR-20 s	2 (20%)	8 (80%)
VL-3+3 s	2 (20%)	8 (80%)

QTH: Quartz-tungsten-halogen

performed using a 37 °C hot water tank. To achieve better clinical results, Kodonas et al. (18) simulated microcirculation flow in the pulp chamber by maintaining inflow at a constant 37 °C, which more accurately reflects *in vivo* conditions (29). In our pilot study, it was determined that the physiological temperature in the pulp chamber, which we attempted to adjust only by microcirculation, was very unstable. Therefore, the experimental conditions used to mimic periodontal tissues and regulate the temperature of the environment were adapted using a TCAP (Figure 2). Thus, the temperature in the pulp chamber was consistently maintained at 37±1 °C before the experiment.

In an *in vitro* study by Weerakoon et al. (30), Class-V composite restorations were cured for 40 seconds in premolar teeth. They found that LED light increased the temperature of the pulp chamber less than a halogen lamp. In our study, there was no significant difference in temperature increase between the quartz-tungsten-halogen (QTH) and LED groups in the short- and long-term curing settings (Table 1).

Exposure time is another crucial factor that influences temperature (8,29). During curing of the composite resin, the primary factor that increases temperature is light energy, while the secondary factor is the exothermic heat energy produced during polymerization of the composite resin (31). Total radiation exposures for the short-term setting groups were approximately 12.8, 15, 12, and 9.6 J/cm^2, and those for long-term irradiation groups were double these values. However, the temperature increases did not appear to follow the order of total radiation. This may be due to the fact that the total heat generated is regulated along with a microcirculation effect during different irradiation times. Almost all manufacturers that produce composite materials recommend 40 seconds of curing time. We selected two different exposure times set for each of the curing units, in accordance with manufacturer's instructions. Significant differences in pulp chamber temperature elevations were found among short-term and long-term exposure times in experiments with all curing units ($p<0.001$); this result is consistent with a previous study, except for the WP group (29). Long-term curing times for the QHT-40s, WP-30s, KR-20s and VL-3+3s units resulted in temperature increases >5.5 °C in the pulp chamber. To achieve optimum curing times for QHT-20s, WP-15s, KR-10s and VL-3s, temperature increases in the pulp chamber should be limited to under safe limits (i.e., <5.5 °C).

In this *in vitro* study, which simulated the microcirculation in the pulp chamber at 37 °C, various curing units were used at different time settings, and it was verified whether critical temperature increases in the pulp chamber had reached the 5.5 °C threshold. Although *in vitro* simulation closely approximates physiological conditions, it is not able to fully simulate the *in vivo* environment. Although the pulp microcirculation is kept constant in such *in vitro* studies, factors, such as age and gender, can actually influence pulpal microcirculation volume (32). In addition, the TCAPs that were used in this study to simulate the periodontal tissues may not simulate the *in vivo* environment. Because such studies are not ethical to perform *in vivo*, development of more realistic experimental simulation devices and protocols are anticipated to provide more accurate results.

Conclusion

Long-term curing times with LEDs exceeded critical temperature increases of 5.5 °C in the pulp chamber. Exposure time is an important risk factor for damage to the pulp tissue. Therefore, to prevent-or, at least mitigate-damage to the pulp tissue, short-term light exposure is the safer option.

Ethics

Ethics Committee Approval: This study was approved by the Pamukkale University Ethics Committee of the Faculty of Medicine (approval number: 06, date: 20.04.2017).

Informed Consent: Consent forms stating that the extracted teeth can be used in scientific research were signed by the patients.

Peer-review: Externally and internally peer-reviewed.

Authorship Contributions

Concept: İ.F.E., Design: İ.F.E., Supervision: İ.F.E., Data Collection or Processing: B.Y., Analysis or Interpretation: İ.F.E., Materials: İ.F.E., Literature Search: İ.F.E., Writing: İ.F.E.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

References

1. Zach L, Cohen G. Pulp Response to Externally Applied Heat. Oral Surg Oral Med Oral Pathol 1965; 19: 515-30.
2. Lieu C, Nguyen TM, Payant L. In vitro comparison of peak polymerization temperatures of 5 provisional restoration resins. J Can Dent Assoc 2001; 67: 36-9.
3. Ozturk B, Usumez A, Ozturk AN, Ozer F. In vitro assessment of temperature change in the pulp chamber during cavity preparation. J Prosthet Dent 2004; 91: 436-40.
4. Hussey DL, Biagioni PA, Lamey PJ. Thermographic measurement of temperature change during resin composite polymerization in vivo. J Dent 1995; 23: 267-71.
5. Nomoto R, McCabe JF, Hirano S. Comparison of halogen, plasma and LED curing units. Oper Dent 2004; 29: 287-94.
6. Hofmann N, Markert T, Hugo B, Klaiber B. Effect of high intensity vs. soft-start halogen irradiation on light-cured resin-based composites. Part I. Temperature rise and polymerization shrinkage. Am J Dent 2003; 16: 421-30.
7. Hofmann N, Hugo B, Klaiber B. Effect of irradiation type (LED or QTH) on photo-activated composite shrinkage strain kinetics, temperature rise, and hardness. Eur J Oral Sci 2002; 110: 471-9.
8. Powell GL, Anderson JR, Blankenau RJ. Laser and curing light induced in vitro pulpal temperature changes. J Clin Laser Med Surg 1999; 17: 3-5.
9. Yamaguchi R, Powers JM, Dennison JB. Thermal expansion of visible-light-cured composite resins. Oper Dent 1989; 14: 64-7.
10. Knezevic A, Tarle Z, Meniga A, Sutalo J, Pichler G. Influence of light intensity from different curing units upon composite temperature rise. J Oral Rehabil 2005; 32: 362-7.
11. Weber J, Rumel A, Netto NG. [Measurement of thickness of remaining dentin after cavity preparation. Radiographic and direct methods]. Rev Assoc Paul Cir Dent 1980; 34: 452-61.
12. Hansen EK, Asmussen E. Correlation between depth of cure and temperature rise of a light-activated resin. Scand J Dent Res 1993; 101: 176-9.
13. Al-Qudah AA, Mitchell CA, Biagioni PA, Hussey DL. Thermographic investigation of contemporary resin-containing dental materials. J Dent 2005; 33: 593-602.
14. Raab WH. Temperature related changes in pulpal microcirculation. Proc Finn Dent Soc 1992; 88 Suppl 1: 469-79.
15. Meyer MW. Pulpal blood flow: use of radio-labelled microspheres. Int Endod J 1993; 26: 6-7.
16. Matthews B, Andrew D. Microvascular architecture and exchange in teeth. Microcirculation 1995; 2: 305-13.
17. Kodonas K, Gogos C, Tziafas D. Effect of simulated pulpal microcirculation on intrapulpal temperature changes following application of heat on tooth surfaces. Int Endod J 2009; 42: 247-52.
18. Kodonas K, Gogos C, Tziafa C. Effect of simulated pulpal microcirculation on intrachamber temperature changes following application of various curing units on tooth surface. J Dent 2009; 37: 485-90.
19. Pohto M, Scheinin A. Microscopic Observations on Living Dental Pulp II. The Effect of Thermal Irritants on the Circulation of the Pulp in the Lower Rat Incisor. Acta Odontologica Scandinavica 1958; 16: 315-27.
20. Whitworth JM, Myers PM, Smith J, Walls AW, McCabe JF. Endodontic complications after plastic restorations in general practice. Int Endod J 2005; 38: 409-16.
21. Baldissara P, Catapano S, Scotti R. Clinical and histological evaluation of thermal injury thresholds in human teeth: a preliminary study. J Oral Rehabil 1997; 24: 791-801.
22. Pohto M, Scheinin A. Vital microscopy of the pulp in the rat incisor. VII. Reactions to silicate cements. Suom Hammaslaak Toim 1967; 63: 178-86.
23. Schmalz G, Schuster U, Nuetzel K, Schweikl H. An in vitro pulp chamber with three-dimensional cell cultures. J Endod 1999; 25: 24-9.
24. Uhl A, Volpel A, Sigusch BW. Influence of heat from light curing units and dental composite polymerization on cells in vitro. J Dent 2006; 34: 298-306.
25. Kim S. Microcirculation of the dental pulp in health and disease. J Endod 1985; 11: 465-71.
26. Eldeniz AU, Usumez A, Usumez S, Ozturk N. Pulpal temperature rise during light-activated bleaching. J Biomed Mater Res B Appl Biomater 2005; 72: 254-9.
27. Sulieman M, Addy M, Rees JS. Surface and intra-pulpal temperature rises during tooth bleaching: an in vitro study. Br Dent J 2005; 199: 37-40.
28. Cobb DS, Dederich DN, Gardner TV. In vitro temperature change at the dentin/pulpal interface by using conventional visible light versus argon laser. Lasers Surg Med 2000; 26: 386-97.
29. Hannig M, Bott B. In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources. Dent Mater 1999; 15: 275-81.
30. Weerakoon AT, Meyers IA, Symons AL, Walsh LJ. Pulpal heat changes with newly developed resin photopolymerisation systems. Aust Endod J 2002; 28: 108-11.
31. Lloyd CH, Joshi A, McGlynn E. Temperature rises produced by light sources and composites during curing. Dent Mater 1986; 2: 170-4.
32. Kim D, Park SH. Effects of age, sex, and blood pressure on the blood flow velocity in dental pulp measured by Doppler ultrasound technique. Microcirculation 2016; 23: 523-9.