2020

Heat Generation of Bulk-fill Composites Polymerized by Multipeak Versus Single Peak Light Curing Units

Fahad Baabdullah
Nova Southeastern University

HEAT GENERATION OF BULK-FILL COMPOSITES POLYMERIZED BY MULTIPEAK VERSUS SINGLE PEAK LIGHT CURING UNITS

FAHAD BAABDULLAH. B.D.S.

A THESIS PRESENTED TO THE FACULTY OF THE COLLEGE OF DENTAL MEDICINE OF NOVA SOUTHEASTERN UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

JULY 2020

HEAT GENERATION OF BULK-FILL COMPOSITES POLYMERIZED BY MULTIPEAK VERSUS SINGLE PEAK LIGHT CURING UNITS

By

FAHAD BAABDULLAH, B.D.S.

A thesis submitted to the College of Dental Medicine of Nova Southeastern University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Cariology and Restorative Dentistry

College of Dental Medicine

July 2020

Approved as to style and content by:

APPROVED BY: ____

Sibel A. Antonson, D.D.S., Ph.D., M.B.A. (Mentor) **Date**

APPROVED BY: ____

Evren Kilinc, D.D.S., Ph.D., M.P.H. (Committee Member) **Date**

APPROVED BY: ____

Cristina Garcia-Godoy, D.D.S., M.P.H., C.C.R.P. (Committee Member) **Date**

APPROVED BY: ____

Steven Kaltman, D.M.D., M.D., F.A.C.S. (Dean) **Date**

Health Professions Division
Department of Cariology and Restorative Dentistry
College of Dental Medicine

STUDENT NAME: Fahad Baabdullah, B.D.S.

STUDENT E-MAIL ADDRESS: fb409@mynsu.nova.edu

STUDENT TELEPHONE NUMBER: (352)-665-3566

COURSE DESCRIPTION: Master of Science

TITLE OF SUBMISSION: Heat Generation of Bulk-Fill Composites Polymerized by Multipeak Versus Single Peak Light Curing Units

DATE SUBMITTED: July 2020

I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.Sc. degree and for this assignment.

STUDENT SIGNATURE: ____

Fahad Baabdullah, B.D.S. **Date**

DEDICATION

I dedicate this thesis to Allah, Almighty God my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. I also dedicated this thesis to my parents, my wife, my children and my sisters, who were always there to support me and encourage me throughout my journey. Thank you, you were the big reason behind my success. My love for you all can never be quantified.

ACKNOWLEDGMENT

I would like to acknowledge the following individuals:

- Dr. Sibel Antonson, for chairing my thesis committee. I am so grateful and honored for all of your guidance, tremendous support and patience throughout this process; from grant proposal to completion of the master's thesis.

- Dr. Cristina Garcia-Godoy and Dr. Evren Kilinc, for serving on my committee. Thank you for your guidance and assistance with the master's project.

- Dr. Patrick Hardigan, for the assistance in the statistical analysis.

- Ria Achong-Bowe, thank you for your great help and all your assistance in the Bioscience Research Center at Nova Southeastern University.

- Mrs. Patrice Stack, for all your help with the administrative part of my thesis.

ABSTRACT

HEAT GENERATION OF BULK-FILL COMPOSITES POLYMERIZED BY MULTIPEAK VERSUS SINGLE PEAK LIGHT CURING UNITS

DEGREE DATE: JULY 2020

FAHAD BAABDULLAH, B.D.S.

Nova Southeastern University

Directed by:

Dr. Sibel A. Antonson, Assistant Dean for Research and Development, College of Dental Medicine

Dr. Evren Kilinc, Cariology and Restorative Dentistry, College of Dental Medicine

Dr. Cristina Garcia-Godoy, Cariology and Restorative Dentistry, College of Dental Medicine

Background: Multipeak light-curing units (LCUs) are gaining popularity due to potential need to activate different photoinitiators. One of the risks associated with using LCUs is heat generation which can reach the pulp chamber through restorative materials and may cause an adverse pulp reaction. However, there is a limited data on heat generation potential of multipeak as compared to single peak LCUs.

Objective: Evaluate the difference in heat generation, and transmission from single peak versus multipeak LED-LCUs through dentin and different bulk-fill resin-based composites (BFRCs) at pulpal wall (PW).

Materials and Methods: A single extracted sound human molar was used for standardized test set-up. A tunnel was prepared lingually to expose buccal-pulpal-axial-wall, and a box

cavity, measured (2.5x3.5x3mm), was prepared buccally for BFRCs placement. A 0.5 mm remaining dentin thickness was left between PW and buccal cavity preparation. The PW was reflected to thermal-infrared-camera (Thermovision-A320, FLIR) via minimal-energy-loss mirror ($\lambda/4$ First Surface Mirror, Edmund Industrial Optics) to measure temperature changes on PW indirectly and on BFRC directly. Four multipeak LCUs (Bluephase G2, Ivoclar Vivadent; Bluephase PowerCure, Ivoclar Vivadent; D-Light Pro, GC Europe; Valo Cordless, Ultradent) and one single peak LCU (Demi Ultra, Kerr) were compared when photopolymerizing two BFRCs (Tetric EvoCeram Bulk Fill (TEB), Ivoclar Vivadent; Filtek One Bulk Fill Restorative (FOB), 3M ESPE). No bonding agent was used for easy removal of the BFRC after each cycle. BFRCs were photopolymerized for 10 seconds, and PW and BFRCs temperatures were recorded for 90 seconds. Four measurements were calculated for each LCU/BFRC combination: baseline to maximum temperatures (ΔT), time to reach maximum temperature (t), duration of the temperature above threshold (Δt), and heat transmission rate to PW (Q) using ThermoVision®ExaminIR™ (FLIR systems) software. Data were statistically analyzed using One-way ANOVA ($p<0.001$), Tukey's post-hoc tests, and Tukey HSD tests.

Results: In both BFRC groups, Valo Cordless, followed by Demi Ultra, generated significantly lower ΔT than other LCUs. Bluephase G2 has a significantly longer duration (Δt) in both BFRC groups. No significant difference was noted in (t) between groups. TEB had significantly higher temperature values (ΔT) and longer duration (Δt) when photopolymerized with all LCUs except Valo Cordless. FOB showed a significantly lowest Q when photopolymerized with Valo Cordless, while TEB showed the lowest Q when photopolymerized with Demi Ultra.

Conclusion: Some LCUs can induce more heat generation and transmission than others and can impose an additional risk of pulp injury, but not necessarily between multipeak and single peak. Different BFRCs can heat up differently, and consequently can impose an additional risk of pulp injury.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

BFRC: Bulk-fill resin-based composites

CQ: Camphorquinone

FOB: Filtek™ One Bulk Fill Restorative

LCU: Light Curing Unit

LED: Light Emitted Diode

RBC: Resin-based Composite

TEB: Tetric EvoCeram® Bulk Fill

CHAPTER 1: INTRODUCTION

Heat generation is one of the main aspects to consider during dental treatments. Many dental procedures generate heat, which can increase the temperature of the tooth surface. These procedures, including tooth preparation using laser or diamond burs,[1,2] fabrication of provisional crowns,[3-5] light-acceleration of some teeth whitening materials,[6,7] the exothermic reaction from resin-based composite (RBCs) during photopolymerization using light-curing units (LCUs),[8,9] may eventually lead to an increase in the dental pulp temperature and consequently, can cause reversible or irreversible pulp damage. Multiple studies had examined the effect of heat on pulpal tissues. Zach et al.[10] in their classic in-vivo study on monkey's teeth, reported that the increase in pulpal temperature of 11.1°C and 5.5°C lead to irreversible pulp damage in 60% and 15% respectively. Lynch et al.[11] also confirmed similar findings in their ex-vivo human teeth study. They reported that an increase of 5.5°C in pulpal temperature for more than 40 seconds led to an immediate decrease in cell number, and they recommended to keep the temperature increase at 5°C or below. However, some controversy exists as some reported an average increase of human pulp temperature to 11.2°C did not cause damage to the pulp.[12] Regardless, it is agreeable that temperature increase within the pulp chamber can pose a threat to the vitality of the dental pulp, and many heat studies have considered the 5.5°C threshold as a safe threshold. However, many dental procedures can easily exceed the 5.5°C threshold, including the modern Light Emitting Diode (LED) LCUs.[13,14]

1.1 Light Curing Units

In the field of modern restorative dentistry, LCUs have become an essential component to photopolymerize various dental materials, including direct and indirect restorations,

adhesives, sealants, resin-cements, and light-acceleration of some teeth whitening procedures. During the past decades, LCUs were introduced and went under numerous developments and advancements, starting with the introduction of the first Ultra Violet dental light curing that was used to place the first light-cured restoration in 1973.[15,16] Not too late after that, the visible-light curing systems such as plasma arch, argon laser, and quartz-tungsten halogen (QTH) lights were introduced to the dental market. Argon lasers were expensive and were heavy. Plasma arch was advertised to have sub-seconds curing time; however, it required to be highly filtered to remove infrared (IR) and ultraviolet (UV) radiation, so both plasma arch and argon laser LCUs did not last long in the dental market. On the other hand, QTH LCUs were the mainstream of dental LCUs until the late 1990s and early 2000s. These units consist of a QTH bulb with a filtering mechanism. Only 0.5% of the total radiating energy from the QTH bulb is useful for the photopolymerization of dental composites; the rest is emitted as IR energy that causes heat generation at the target. The filtering mechanism comprised of a heat-absorbing glass that reduces the passage of IR energy to dental composite and tooth and a separate bandpass filter that allows only a narrow useful spectral emission of visible light between 400-500nm, which matches the maximum absorbance of photoinitiators.[17]

The QTH LCUs were considered a broad-banded in its spectral emission that can activate a wide range of photoinitiators. However, these units required a noisy fan for cooling, were not energy-efficient with limited portability, and has a relatively short bulb lifetime.[18] The next generation of LCU came with the invention and evolution of Light Emitted Diode (LED) technology over the past decades. The technology of LED existed in other industries long before dentistry, and it was not until 1990s that high-intensity blue LED was invented, and researchers in dental field started to incorporate them into dental LCU models.[19-23] These

early models with the blue-LED were successful in photo-activating camphorquinone (CQ), the most frequently used photoinitiator, since they have a blue emission spectrum (450-475 nm) closely match the absorption profile of CQ that has maximum absorbance at (λ_{max}) at 468 nm.[18,24-27] The LED technology is more promising than other LCUs since it does not need filtering mechanism, is more energy efficient in photon generating ability, can be battery-operated and portable, and has a long working life compared to filament and spark-based light sources.[18,28,29]

Starting in early 2000s, early commercial Light Emitted Diode (LED) LCUs were introduced to the market starting with LUXoMAX® (Akeda Dental, Lystrup, Denmark) and followed by other manufacturers.[30] These units have multiple single-emitting blue LED elements (7-64 chips), and each chip can provide between 30 to 60 mW, however, this generation of LCUs had significantly less radiant power output, compared to the widespread QTH LCUs, and had suffered from poor battery performance. The second generation of LED LCUs incorporated an evolved high-power LED chips that allowed a significant increase in the radiant power output compared to the first generation.[26,29] The radiant power output of this generation emitted number of photons within the absorption range of CQ, more than QTH or plasma arch lights.[26] It also has an improved battery technology using NiMH battery sources. However, it maintained the same blue spectral emission (450-470 nm) as the first generation. These LCUs are known as single peak LCUs.

Nevertheless, as manufacturers incorporated more than only CQ as a photoinitiator, the need for broader spectrum LCU led to the development of the third generation LED LCUs. The third generation LCUs incorporated an additional violet LED chip/s which in combination with the blue LED chip can emit photons at 380- to 500- nm emission spectrum.[31,32] These

LCUs are known as multipeak LCUs.[26,30] The LED LCUs, especially the second and third generations, have successfully taken the place of the older LCUs, owing to their efficient energy consumption, smaller and portable designs, and their ability to produce higher radiant emittance output.

1.2 Photoinitiators

CQ has been known as the most widely used photoinitiator in RBCs since its invention by Dart and Nemcek in 1971,[33] with an absorption range that fell into the blue wavelength of 425-495 nm, and wavelength of maximum absorbance (λ_{max}) of 468 nm. CQ is a bright canary yellow, and only a portion of it utilized during photopolymerization, leaving a residue that results in undesirable yellowish colored restorations.[18,34] With the increasing demand for achieving esthetic RBCs restorations that match the desirable white or translucent shade of dentition nowadays, a reduction in the concentration of CQ with introduction of other co-initiators has been proposed.[35] This process helped to decrease the yellowish effect and increase the efficiency of photopolymerization. Lucirin® TPO (2,4,6-Trimethylbenzoyl-diphenylphosphine oxide) is an example of these photoinitiators with absorption range into the violet wavelengths at 380–420 nm (λ_{max}= 385 nm). Lucirin® TPO is added to the CQ to reduce initial yellowness and color change after curing, and to increase the photopolymerization efficiency.[36,37] Another photoinitiator with a broader band absorption spectrum 390-460 nm (λ_{max}= 410 nm) known as PPD (1-phenyl-1,2-propanedione) was introduced to the dental field in 1999, and in combination with CQ, it yielded an enhanced resin polymerization and reduced the residual yellow color of the restorative materials.[35,38] Recently, a new photoinitiator, Ivocerin® (bis-(4-methoxybenzoyl)diethylgermane) has been developed to provide a broader spectrum of short-wave absorption (390-445nm) (λmax= 408 nm). Furthermore, Ivocerin®

has intensive absorption of light, high photo-reactivity, and excellent bleaching behavior to RBCs comparing with CQ.[18,39]

1.3 Bulk-fill Resin-based Composites

Recently, Bulk-fill RBCs have been introduced to the market with claims of ability to achieve a depth of cure of up to 4 – 5 mm or more, low polymerization shrinkage, and overcome the time-consuming incremental technique of conventional RBCs.[40] The advancements in photoinitiator technology, along with the optimization of filler and matrix properties, helped in the development of bulk-fill RBCs.

Different methods have been used to achieve these properties, including the use of highly photo-reactive photoinitiators such as Ivocerin in Tetric EvoCeram Bulk-fill.[39] Another method was by applying chemical modification to monomers, such as Filtek One Bulk Fill Restorative, which incorporated Aromatic Urethane dimethacrylate (AUDMA) and Addition-Fragmentation Monomer (AFM) to achieve up to 5 mm placement.[41] Another example include Venus Bulk Fill (Heraeus Kulzer GmbH, Hanau, Germany) and SureFil SDR Flow (SDR; Dentsply Caulk, Milford, DE, USA) which have more translucent matrix that permit deeper penetration of light.[42,43] On the other hand, SonicFill Composite System (Kerr, Orange, CA, USA) have a refractive index matching of matrix and filler with enhanced curing mechanism allowing for depth of cure up to 5 mm.[44]

The need to activate different photoinitiators (TPO and Ivocerin®) has driven the production of multipeak LCUs that incorporated a broader wavelength spectrum. However, the use of multipeak LCUs has been reported to be beneficial to photopolymerized RBCs that have photoinitiators other than CQ, but not essential.[45]

1.4 Measurement of Teeth's Thermal Behavior

Different instruments and methods have been reported in the literature to measure and quantify the thermal behavior of dental structures, such as thermocouple devices,[11,46] thermal infrared camera,[1,47-50] flash laser methods,[51] differential scanning calorimeter.[52] Both flash laser method and differential scanning calorimeter required samples to be prepared with well-specified dimensions and thickness, and require more training to operate the equipment. Thermocouples are inexpensive and easy to use, however, they need to be in perfect contact with tooth structure for accurate measurement, and it cannot record temperature in more than a specific point. The infrared camera offers multiple advantages over thermocouple devices, through its ability to capture hundreds of temperatures readings simultaneously in a continuous video format without contact. It allows hundreds of temperature readings per frame on a surface rather than in a point, and can reveal more detailed information about the dynamic distribution and changes in temperature on the measured surface.

1.5 Innovation

According to manufacturers, the contemporary LED LCUs are capable of generating high radiant emittance output which can reach to 3,000-6,000 mW/cm^2. Most of the LED LCUs are capable of producing single peak light while a couple of the LED LCUs in the market can produce a multipeak light. However, the integration of more LED chips along with high radiant emittance output can cause a higher temperature rise within the pulpal tissue.[53] To the best of our knowledge, although both LCUs generate heat during the photopolymerization cycle, no study has evaluated the difference between single peak and multipeak LCUs in heat diffusion and transmission to the pulp chamber. This study aims to investigate the difference between single peak and multipeak LCUs in heat diffusion and transmission to the pulp chamber

through different bulk-fill RBCs, which may cause damage to the pulp tissue. Thus, the proposed study represents a conceptual novelty in the study of LED LCUs for their possible impact on pulp tissue vitality.

1.6 Aim of the study

The aim of this study is to evaluate the difference in heat generation, and transmission from single peak versus multipeak LED LCUs through the dentin and different bulk-fill RBCs at the pulpal wall.

The specific aims of the study are:

1- To evaluate the difference in heat generation between single peak versus multipeak LED LCUs at the pulpal wall when photopolymerize different bulk-fill RBCs.

2- To evaluate the difference in heat generation between different bulk-fill RBCs when photopolymerized with the same LCU.

3- To evaluate the difference in the heat transmission between single peak versus multipeak LED LCUs through the dentin when photopolymerize different bulk-fill RBCs.

1.7 Null Hypotheses

The null hypotheses for this study are:

1. There will be no difference in heat generation between single peak versus multipeak LED LCUs at the pulpal wall when photopolymerize different bulk-fill RBCs.
2. There will be no difference in heat generation between different bulk-fill RBCs when photopolymerized with same LCU.

3. There will be no difference in the heat transmission between single peak versus multipeak LED LCUs through the dentin when photopolymerize different bulk-fill RBCs.

1.8 Location of the Study

Design, preparation, data collection, and analysis for this study took place at:

Bioscience Research Center, Room 7356

Nova Southeastern University

Health Professional Division

College of Dental Medicine

3200 South University Drive

Fort Lauderdale, Florida 33328

CHAPTER 2: MATERIAL AND METHODS

2.1 Sample Size Calculation

According to the study conducted by Oberholzer et al.,[54] a single tooth model was used for the study. The single tooth model ensured standardization of the measurement and eliminated the variable associated with using multiple teeth. The sample size was determined by power calculation using the results by Oberholzer et al.[54] expecting a medium effect, targeting alpha of 0.05, and a power of 80%.Ten samples (n=10) were prepared for each experimental condition composed of LCU/RBC combination, giving a total of 100 samples (n=100).

2.2 Study groups, Specimen Preparation, and Thermal Apparatus Set-up

A modified experimental design and set-up based on the study conducted by Kilinc et al.[1] was used in the study. All procedures and measurements were performed by a single operator (Dr. Fahad Baabdullah) to ensure the standardization of the application and measurement procedures. In this study, the independent and dependent variables are described below

2.2.1 Variables and Study Groups:

2.2.1.1 Independent Variables: Bulk-fill RBCs and LED LCUs

A total of two bulk-fill composites were photopolymerized using five LED LCUs

Bulk-fill RBCs: (Table 1)

1. Filtek One Bulk Fill Restorative (3M ESPE Dental Products, St. Paul, MN, USA)
2. Tetric EvoCeram Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein)

Table 1: Bulk-Fill RBCs used in the study

Composite (code) (Lot no.)	Type	Composition	Filler	Shade	Photoinitiator	Manufacturer
Filtek™ One Bulk Fill Restorative (FOB) (NA54510)	Nano-hybrid composite	AFM AUDMA UDMA DDDMA	76.5 wt.% (58.4 vol%) Non-agglomerated/non-aggregated silica (20 nm)/zirconia (4-11 nm) Aggregated zirconia/silica cluster filler YbF_3 filler agglomerate 100nm particles	A1	Camphorquinone	3M ESPE Dental Products, St. Paul, MN, USA
Tetric EvoCeram® Bulk Fill (TEB) (Y27607)	Nano-hybrid composite	Bis-GMA Bis-EMA UDMA	76–77 wt.% (53–54 vol%) Barium aluminium silicate glass (0.4-0.7 µm) YbF_3 (200 nm) Spherical mixed oxide and copolymers (160 nm)	^{IV}A	Camphorquinone Acyl phosphine oxide (Lucirin TPO) Ivocerin®	Ivoclar Vivadent, Schaan, Liechtenstein

AFM, addition-fragmentation monomer; AUDMA, aromatic urethane dimethacrylate; Bis-EMA, ethoxylated bisphenol A dimethacrylate; Bis-GMA, bisphenol A-diglycidyl dimethacrylate; DDDMA, 1, 12-dodecanediol dimethacrylate; UDMA, urethane dimethacrylate; YbF_3, ytterbium trifluoride;

LED LCUs: (Table 2)

1. Bluephase PowerCure (Ivoclar Vivadent, Schaan, Liechtenstein) on High Power mode at 1200 mW/cm^2 (Multipeak).
2. Bluephase G2 (Ivoclar Vivadent, Schaan, Liechtenstein) on High Power mode at 1200 mW/cm^2 (Multipeak).

3. Valo Cordless (Ultradent Products, Inc., South Jordan, UT, USA) on Standard Power mode at 1,000 mW/cm^2 (Multipeak).
4. D-Light Pro (GC Europe N.V., Leuven, Belgium) on High Power mode at 1,400 mW/cm^2 (Multipeak).
5. Demi Ultra (Kerr Corp., Orange, CA, USA) at 1,100-1,330 mW/cm^2 (Multipeak).

Table 2: Light Curing Units used in the study:

LCUs (S/N)	**Manufacturer**	**Light Type**	**Mode**	**Expected Radiant Emittance (mW/cm^2)**
Bluephase® G2 (P626170S705660)	Ivoclar Vivadent, Schaan, Liechtenstein	Multipeak (385-515 nm) Peak at 410 nm and 470 nm	High Power	1,200
Bluephase® PowerCure (1428001929)	Ivoclar Vivadent, Schaan, Liechtenstein	Multipeak (385-515 nm) Peak at 410 nm and 470 nm	High Power	1,200
D-Light® Pro (1846239)	GC Europe N.V., Leuven, Belgium	Multipeak (400 - 480nm) Peak at 400-405 nm and 460-465nm	High Power	1,400
Demi™ Ultra (787-002-423)	Kerr Corp., Orange, CA, USA	Single peak (450-470 nm)	--	1,100-1,330
Valo™ Cordless (C50461)	Ultradent Products, Inc., South Jordan, UT, USA	Multipeak (395-480 nm) Peak at 395-415 nm and 440-480nm	Standard Power	1,000

2.2.1.2 Dependent Variables:

The dependent variables in the study were the temperature and time measurement conducted for each sample as follow:

1. Amount of temperature increase from baseline to the maximum temperature (ΔT.
2. Time to reach maximum temperature (t).

3. Duration of the temperature above the threshold (Δt).
4. Heat transmission rate to the pulpal wall (Q).

2.2.1.3 Study Groups:

(Table 3) illustrate the study groups of the study:

Table 3: Study Groups

Composite	Sample Size (n)	LCU	Radiant Emittance (mW/cm^2)	LCU Type
Filtek™ One Bulk Fill Restorative	10	Bluephase G2	1,200	Multipeak
Filtek™ One Bulk Fill Restorative	10	Bluephase PowerCure	1,200	Multipeak
Filtek™ One Bulk Fill Restorative	10	D-Light Pro	1,400	Multipeak
Filtek™ One Bulk Fill Restorative	10	Valo Cordless	1,000	Multipeak
Filtek™ One Bulk Fill Restorative	10	Demi Ultra	1,100-1,330	Single peak
Tetric EvoCeram® Bulk Fill	10	Bluephase G2	1,200	Multipeak
Tetric EvoCeram® Bulk Fill	10	Bluephase PowerCure	1,200	Multipeak
Tetric EvoCeram® Bulk Fill	10	D-Light Pro	1,400	Multipeak
Tetric EvoCeram® Bulk Fill	10	Valo Cordless	1,000	Multipeak
Tetric EvoCeram® Bulk Fill	10	Demi Ultra	1,100-1,330	Single peak

2.2.2 Tooth Specimen Preparation

Upon Institutional Review Board (IRB# 2019-91) exemption approval, a single non-carious unidentified lower molar human tooth was used. The single-tooth model was used in the study to ensure the standardization of the results.[54,55] The tooth was embedded in fast-setting gypsum material (Mounting Stone, Whip Mix Corp., Louisville, KY, USA) to the level of 3 mm below the cementoenamel junction. On the lingual aspect, a tunnel was created into the pulp chamber to expose the buccal axial pulpal wall (Figure 1). The purpose of the tunnel was to allow

indirect visualization of the pulpal wall by the thermal camera through a minimal-energy-loss mirror (see 2.2.3 Thermal Apparatus Set-up below).

Figure 1: Lingual view of tooth specimen; dotted line, outline of the lingual tunnel; a) Axial Pulpal Wall

On the buccal aspect, a box cavity was prepared (approximately 2.5 mm (W) x 3.5 mm (H) x 3 mm(D)) with slight buccal and occlusal divergence (Figure 2 and Figure 3), leaving an average of 0.5 mm of remaining dentin thickness (RDT) which was confirmed using Iwanson caliper (Hu-Friedy) (Figure 6) and (Figure 7). The box cavity and the tunnel were prepared using a high-speed electric handpiece under copious water with round-end taper diamond bur (Coarse and Fine, Brasseler, Savannah, GA, USA). This box cavity is where the RBCs will be placed and photopolymerized with LED LCUs. The specimen was stored in distilled water in an incubator (37ºC) until testing time. (Figure 6) and (Figure 7) represents a schematic diagram of the specimen preparations.

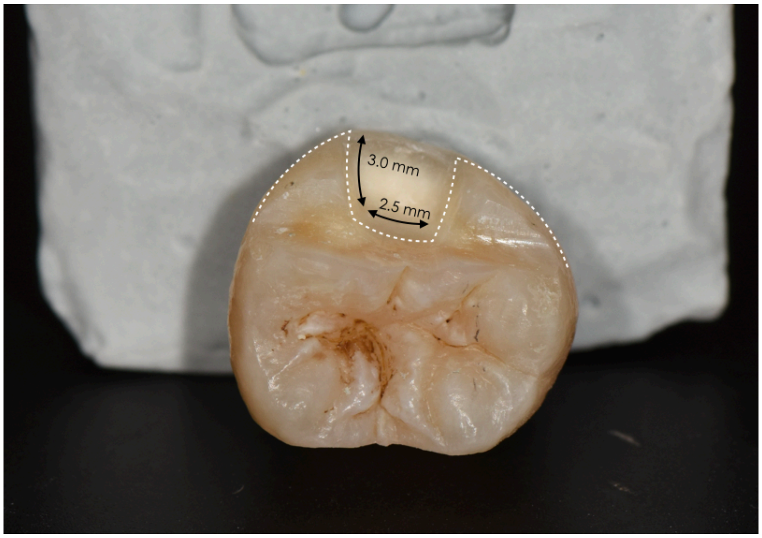

Figure 2: Occlusal view of the buccal box. Buccal box was prepared at 2.5 mm width and 3.0 mm depth

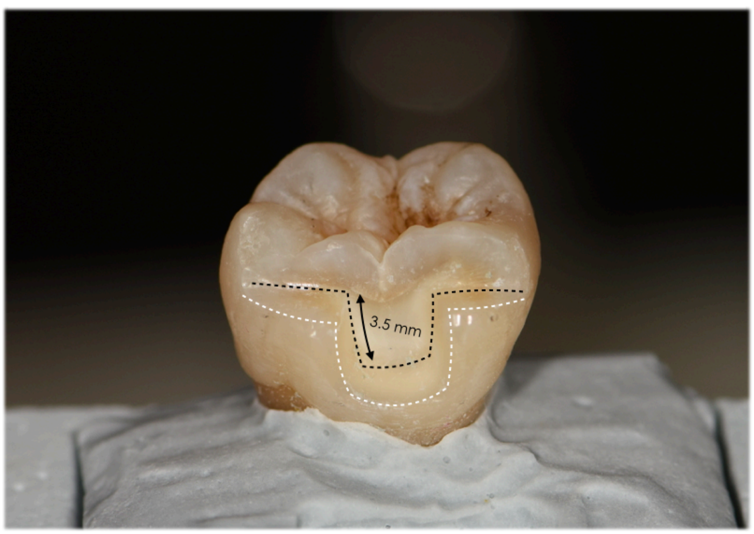

Figure 3: Buccal view of the buccal box. Buccal box was prepared at 3.5 mm height

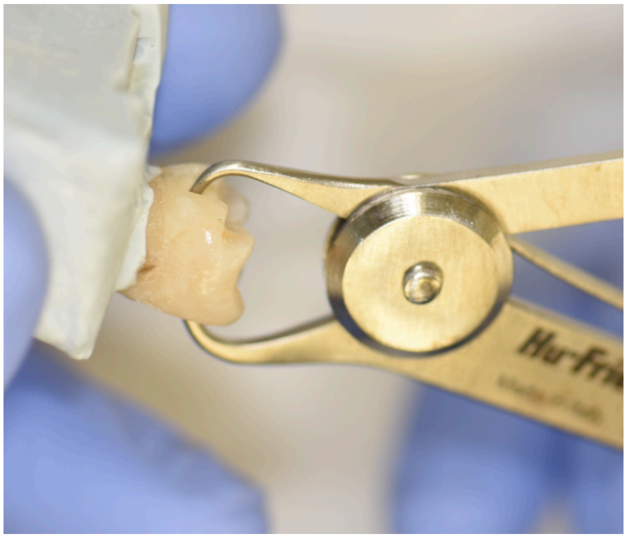

Figure 4: Iwanson caliper confirming the Remaining Dentin Thickness

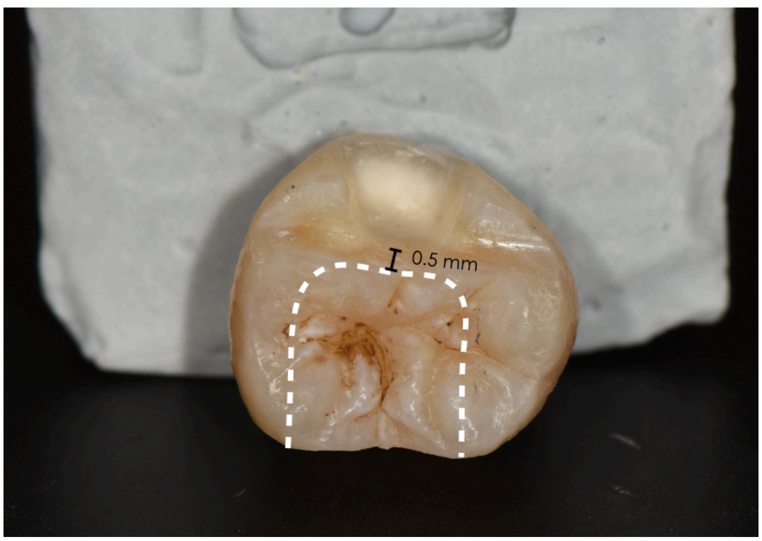

Figure 5: Occlusal view illustrate the tunnel preparation (white dotted line), and the Remaining Dentin Thickness (0.5 mm)

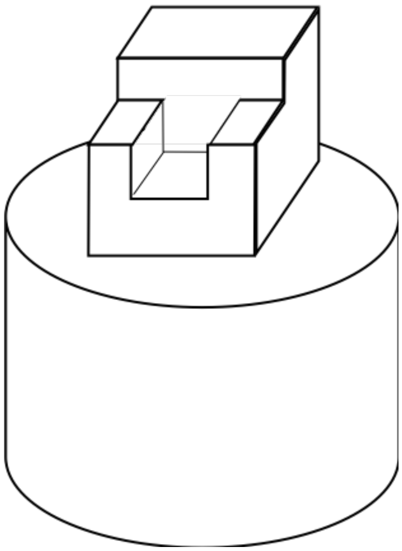

Figure 6: Schematic diagram of the prepared specimen (Buccal)

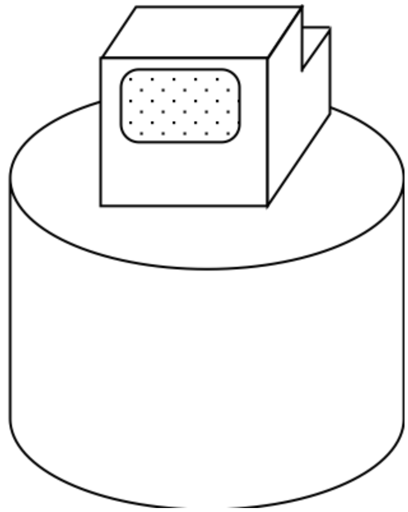

Figure 7: Schematic diagram of the prepared specimen (Lingual)

For each LCU used in the study, a silicon template was fabricated using putty impression material (VP Mix Putty, Henry Schein Inc, NY, USA), and positioned on the buccal aspect of the specimen (Figure 8) to ensure the same repositioning of the LCU tip over RBC (Figure 9).

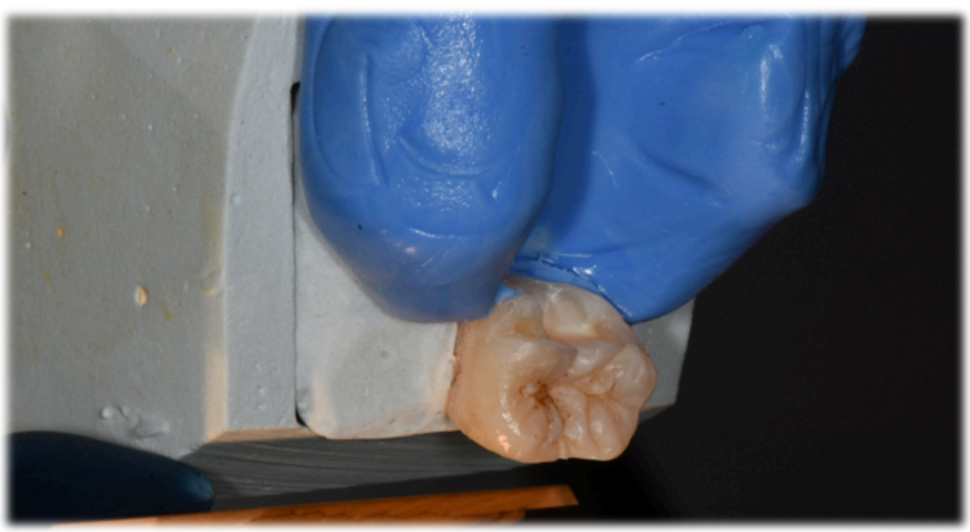

Figure 8: Positioning of the silicon template on the buccal aspect of the specimen

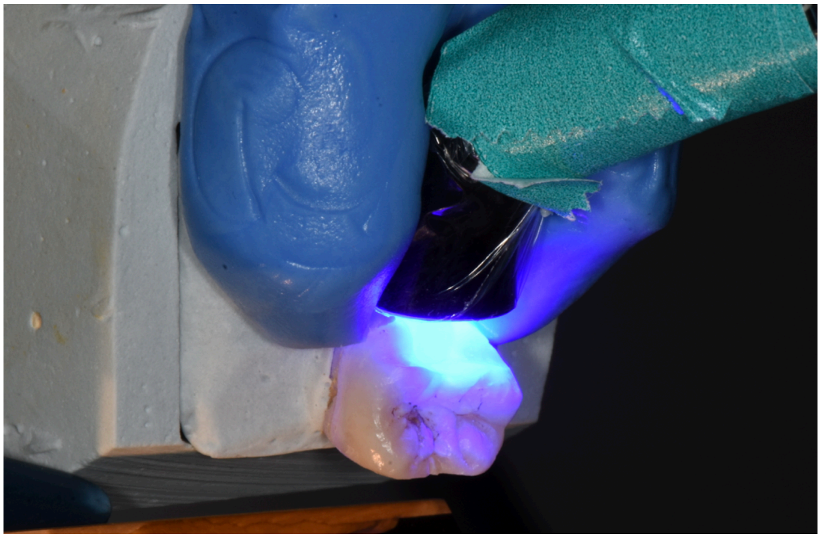

Figure 9: The silicon template allows repositioning of the LCU tip over the RBC for photopolymerization

2.2.3 Thermal Apparatus Set-up

The specimen was mounted horizontally with the buccal surface pointed upward, and the occlusal surface pointed toward the lens of the thermal infrared camera (Thermovision-A320, FLIR Systems, Boston, MA) with a resolution of 320 x 240, used with Macro lens (Close-up Lens 4X-WD 79 mm, FLIR systems). The thermal infrared camera was connected to a Windows laptop for data acquisition and analysis. A minimal-energy-loss mirror (λ/4 First Surface Mirror, NT99-456; Edmund Industrial Optics, Barrington, NJ, USA) was mounted below the specimen and at an angle to allow indirect visualization of the pulpal wall (Figure 10) and (Figure 11). The whole thermal apparatus set-up is depicted in (Figure 12).

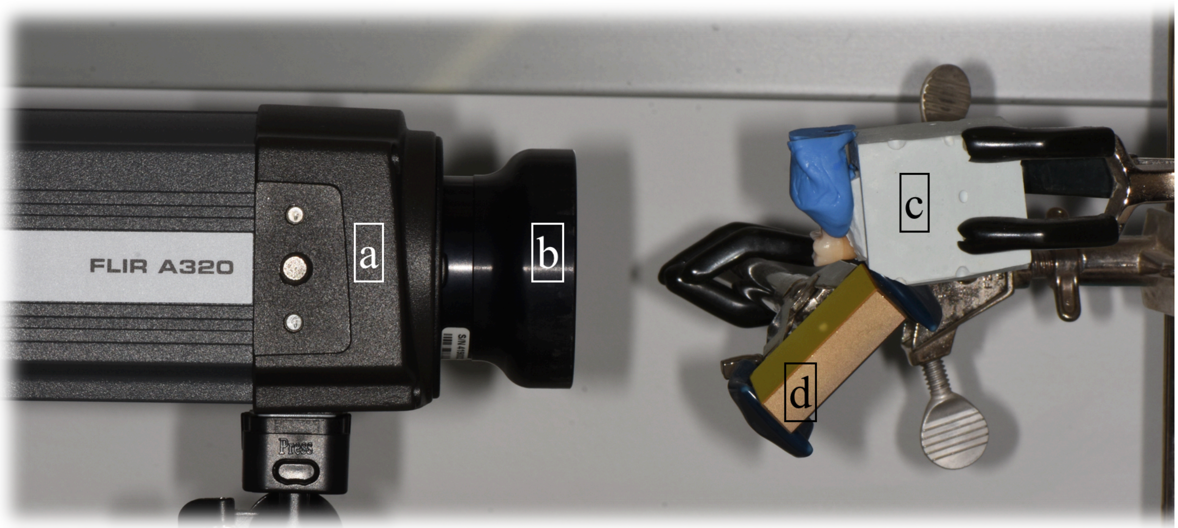

Figure 10: Thermal imaging apparatus. (a) Thermal Infrared Camera; (b) Macro Lens; (c) Specimen positioned in front of the thermal infrared camera; (d) Minimal-energy-loss mirror

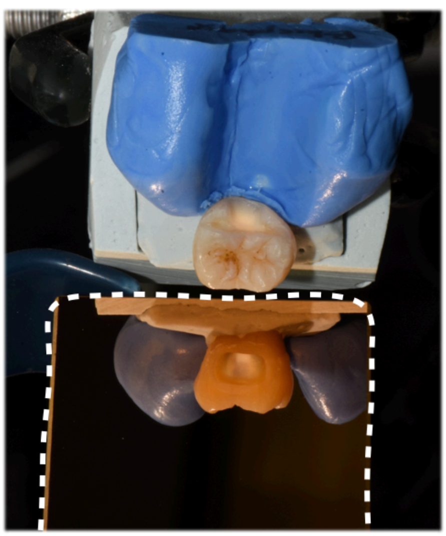

Figure 11: Minimal-energy-loss Mirror (dotted line) allows indirect visualization of the axial pulpal wall, while the RBC in the buccal box can be visualized directly.

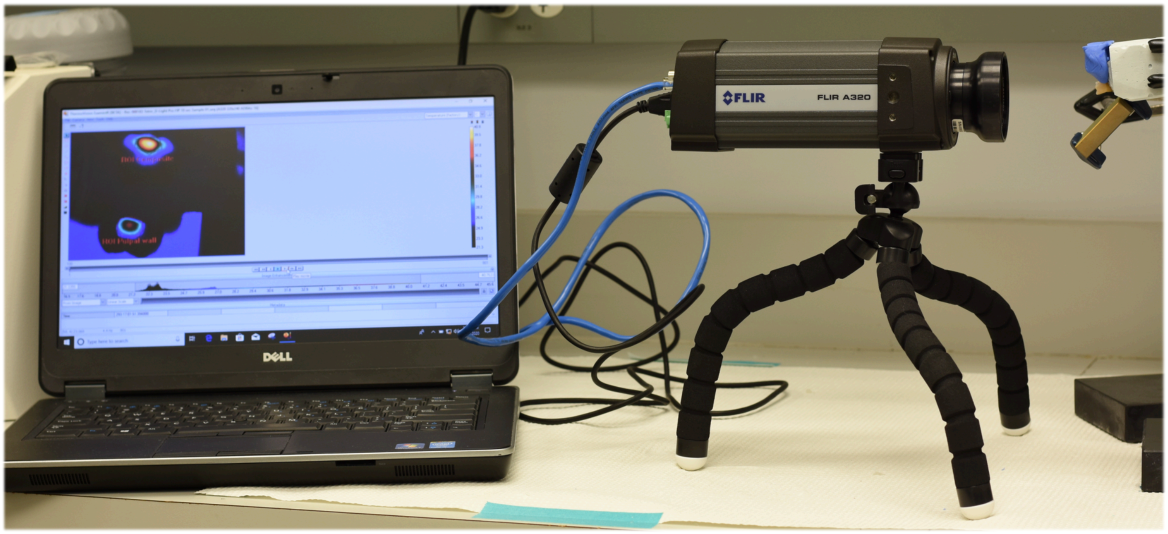

Figure 12: Thermal apparatus set-up

2.3 RBCs Application and Photopolymerization, Recording Cycle, and Data Collection and Analysis of Temperature Changes

2.3.1 RBCs Application and Photopolymerization

The experiment was conducted at controlled room temperature (22 ± 0.5 ºC). Once the temperature of the specimen pulpal wall reached room temperature, bulk-fill RBC was applied into the buccal box cavity, then immediately cured for 10 seconds. The RBC was applied without etching or bonding to allow for easy removal after polymerization and to maintain the same preparation size during the repeated application and removal cycles without damaging the tooth. Each LCU was covered with a protective barrier and positioned as close as possible to the RBC before curing using the silicon template. LCU radiant emittance was measured before each curing cycle using a digital LED curing light radiometer (Bluephase Meter II, Ivoclar Vivadent, Schaan, Liechtenstein) (Figure 13). The measured radiant emittance output, curing time, and sample numbers are listed in (Table 4).

Figure 13: Digital LED curing light radiometer (Bluephase Meter II)

Table 4: Radiant emittance output, curing time, sample numbers

LED LCU	RBCs	Mode	Expected Radiant Emittance (mW/cm²)	Mean ± (SD) of Measured Radiant Emittance (mW/cm²)	Photopolymerization Time
Bluephase® G2	FOB (n=10)	High Power	1,200	1170 (5)	10 seconds
	TEB (n=10)			1179 (3)	
Bluephase® PowerCure	FOB (n=10)	High Power	1,200	951 (3)	10 seconds
	TEB (n=10)			957 (5)	
D-Light® Pro	FOB (n=10)	High Power	1,400	958 (6)	10 seconds
	TEB (n=10			958 (4)	
Demi™ Ultra	FOB (n=10)	--	1,100-1,330	1368 (24)	10 seconds
	TEB (n=10			1350 (16)	
Valo™ Cordless	FOB (n=10)	Standard Power	1,000	1197 (8)	10 seconds
	TEB (n=10			1205 (8)	

FOB, Filtek One Bulk Fill Restorative; TEB, Tetric EvoCeram Bulk Fill

2.3.2 Recording Cycle

The thermal infrared camera was connected to digital software, ThermoVision® ExaminIR™ (FLIR systems), this allows dynamic thermal visualization of the photopolymerization procedure (Figure 14). The photopolymerization procedure was recorded for a total of 90 seconds, started 4-6 seconds before activating the LCU. After each recording cycle was completed, the cured RBC was removed using a cleoid instrument. The specimen was examined under dental loupe 3.5x to ensure complete removal and cleanness of the tooth surface. The specimen was allowed to cool down to room temperature after each application cycle before starting the next cycle for around 10 minutes. A total of ten measurements cycles were performed for each LCU-RBC combination (Table 4).

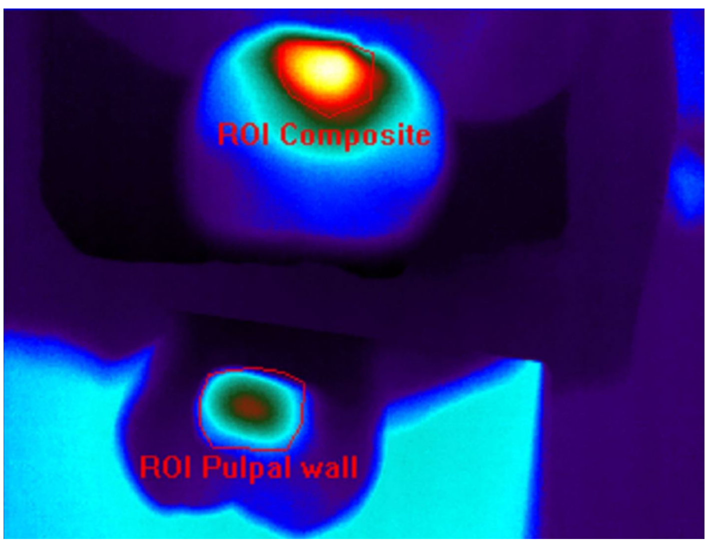

Figure 14: Representative infrared thermogram (Valo - Filtek One Bulk Fill) of the RBCs and pulpal wall during photopolymerization procedure. ROI: Region of interest,

2.3.3 Data Collection and Analysis of Temperature Changes during Photopolymerizing of RBCs

Recordings were analyzed using ThermoVision® ExaminIR™ (FLIR systems). After marking the region of interest (ROI) on the thermographic image, the maximum heat generated on the axial pulpal wall was measured and plotted against time to evaluate the following parameters (dependent variables):

1. Amount of temperature increase from baseline to the maximum temperature (ΔT): recorded by finding the difference between the maximum temperature recorded on the pulpal wall after LCU activation, and the average baseline temperature on the pulpal wall before LCU activation the photopolymerization. The maximum temperature was recorded as the peak point where the temperature starts to fall regardless if it is during or after the LCU was turned off (Figure 15).

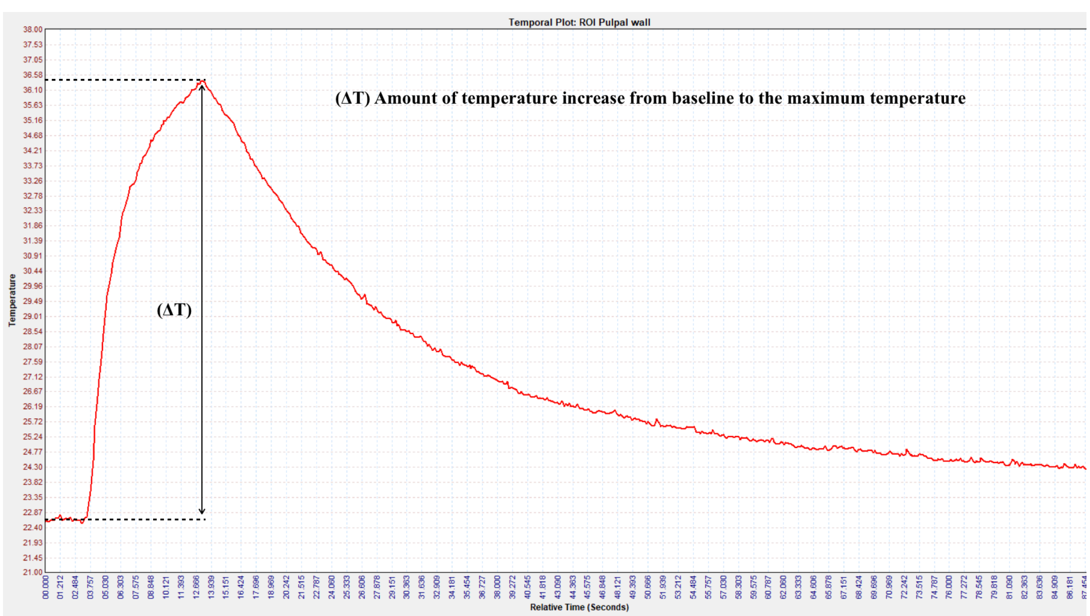

Figure 15: Temporal plot graph shows the calculation of the amount of temperature increase from baseline to the maximum temperature (ΔT)

2. Time to reach maximum temperature (t): recorded by finding the difference between the time of maximum temperature on the pulpal wall, and the time of LCU activation (Figure 16).

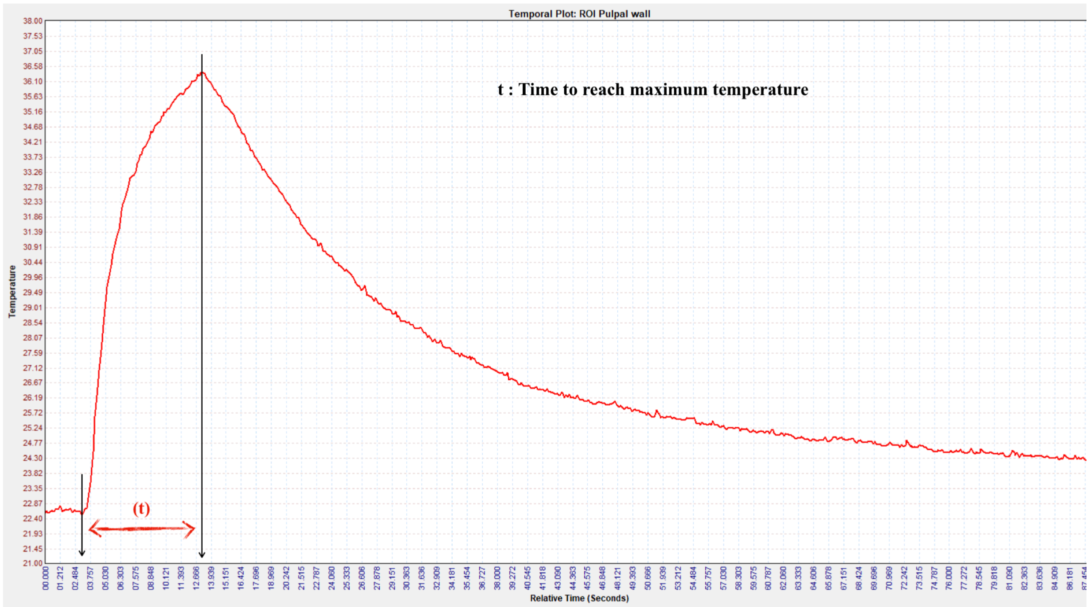

Figure 16: Temporal plot graph shows the calculation of Time to reach maximum temperature (t)

3. Duration of the temperature above the threshold (Δt): recorded by calculating the threshold (threshold defined as a 5.5°C increase from the baseline temperature), then record the duration from which the pulpal wall temperature raised above the threshold until the it fell below the threshold (Figure 17).

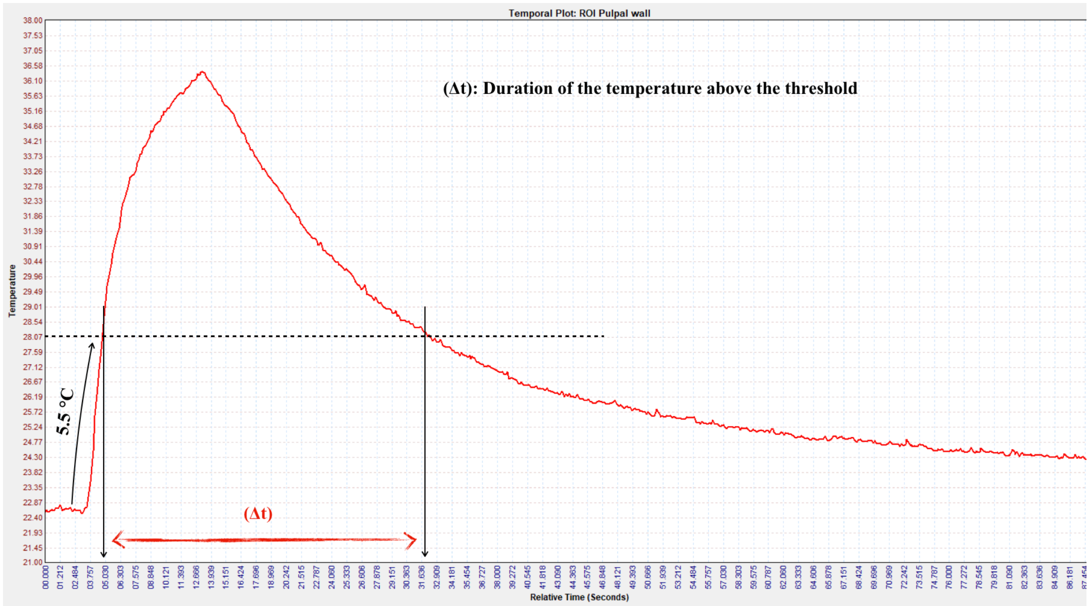

Figure 17: Temporal plot graph shows the calculation of Duration of the temperature above the threshold (Δt)

4. Heat transmission rate to the pulpal wall (Q) (Figure 18): recorded by measuring the maximum temperature on the RBC surface (T_1), then measure the maximum temperature on the pulpal wall at the same point of time (T_2). After that, values were incorporated into the 1-Dimension Thermal Equation using Fourier's Law of Heat Conduction as follow:

$$Q = \frac{kA}{\Delta x}(T_1 - T_2)$$

Where:

- *k*= Thermal conductivity of Dentin ($057 \text{x} 10^{-3}$ W/mm.C) [56]
- *A*= Cross sectional area of the tooth between RBC and Pulpal Wall (3.5 mmx 2.5mm = 8.75 mm^2)
- *Δx*= Remaining Dentin Thickness (0.5 mm)

- T_1= Maximum temperature on the RBC surface
- T_2= Maximum temperature on the pulpal wall at the same time of T_1

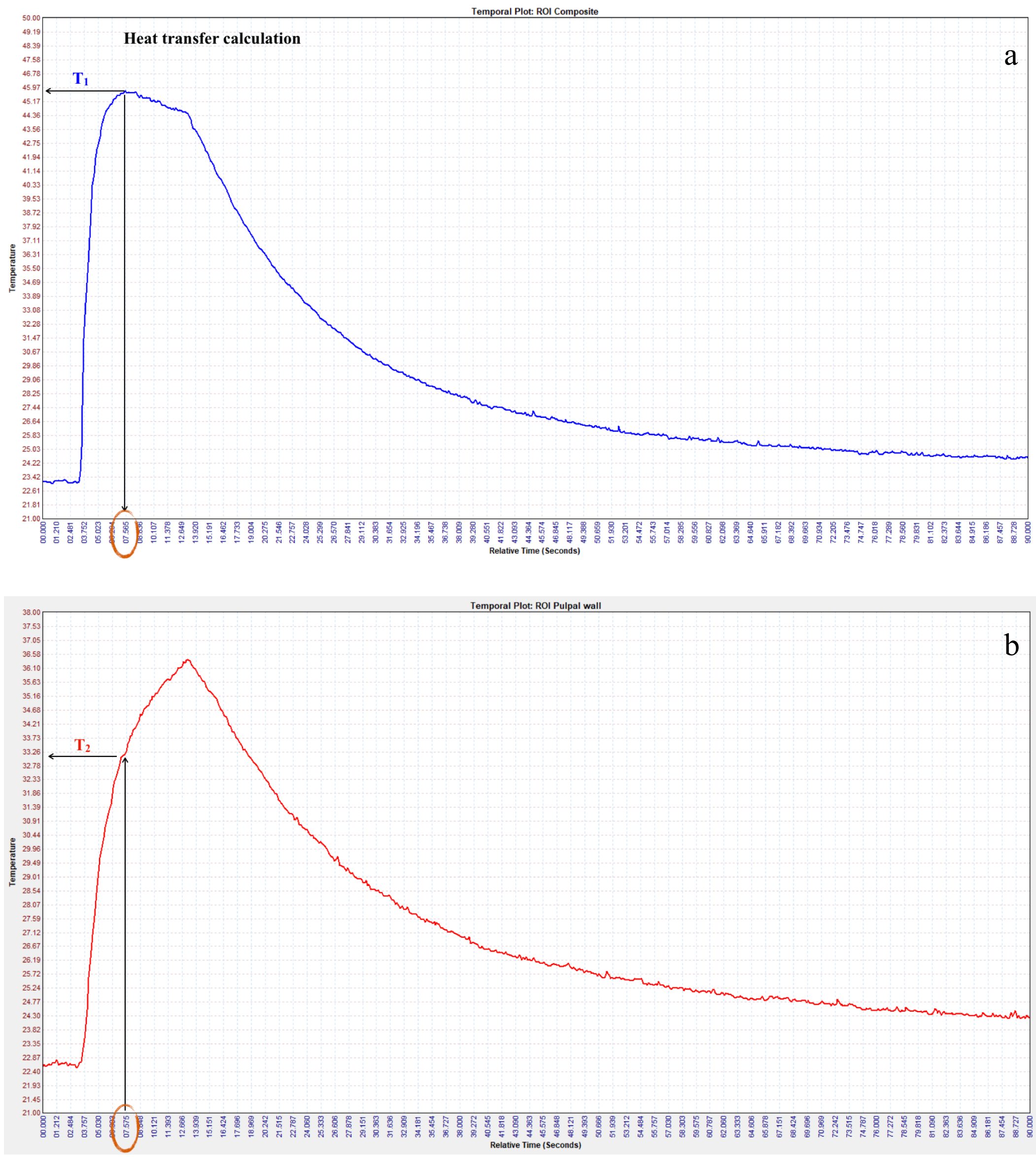

Figure 18: Temporal plot graph shows the calculation of heat transmission rate to the pulpal wall (Q). (a) ROI of the RBC; (b) ROI of the pulpal wall

2.4 Statistical Analysis

Data was first reviewed for outliers and missing data. Descriptive statistics, including means and standard deviations were calculated for all the groups. To test the hypotheses, a one-way ANOVA was used to evaluate the statistical significance of ΔT, t , Δt and Q in respect to different LCUs and RBCs. Multiple comparison tests were conducted using Tukey adjustment if the groups were found to be statistically significantly different. RStudio and R 3.2.2 was used for all statistical analysis, and significance was accepted at $p < 0.05$.

CHAPTER 3: RESULTS

3.1 Analysis of the Amount of Temperature Increase from Baseline to the Maximum Temperature (ΔT)

A one-way ANOVA was conducted to determine if the temperature increase from baseline to the maximum temperature was different by the five LCUs and the two RBCs. A significant statistical difference was noted between the groups as determined by one-way ANOVA ($F(9,90)=154.9$, $p<0.001$).

Among the Filtek One Bulk Fill RBC groups, Tukey's post-hoc test revealed that multipeak Valo Cordless LCU (8.90 ± 0.40 °C) and single peak Demi Ultra LCU (8.97 ± 0.43 °C) generated statistically significant lower heat compared to the other multipeak LCUs. While the multipeak Bluephase G2 (11.44 ± 0.18 °C) generated statistically significant the highest heat.

Among the Tetric EvoCeram Bulk Fill RBC groups, Tukey's post-hoc test revealed that the multipeak Valo Cordless LCU (9.46 ± 0.76 °C) has statistically significant lowest heat generation among the LCUs. The single peak Demi Ultra LCU (10.95 ± 0.47 °C) generated statistically significant higher heat than Valo Cordless, but lower than the rest of the LCUs. The multipeak Bluephase G2 (13.93 ± 0.37 °C) generated statistically significant highest heat (Figure 19) and (Figure 20).

Additionally, Tetric EvoCeram Bulk Fill RBC groups exhibited a statistically significant higher temperature rise than Filtek One Bulk Fill RBC when photopolymerized by Bluephase G2, Bluephase PowerCure, D-Light Pro and Demi Ultra. However, there was no statistical difference between the two RBCs when photopolymerized by Valo Cordless LCU. (Table 5)

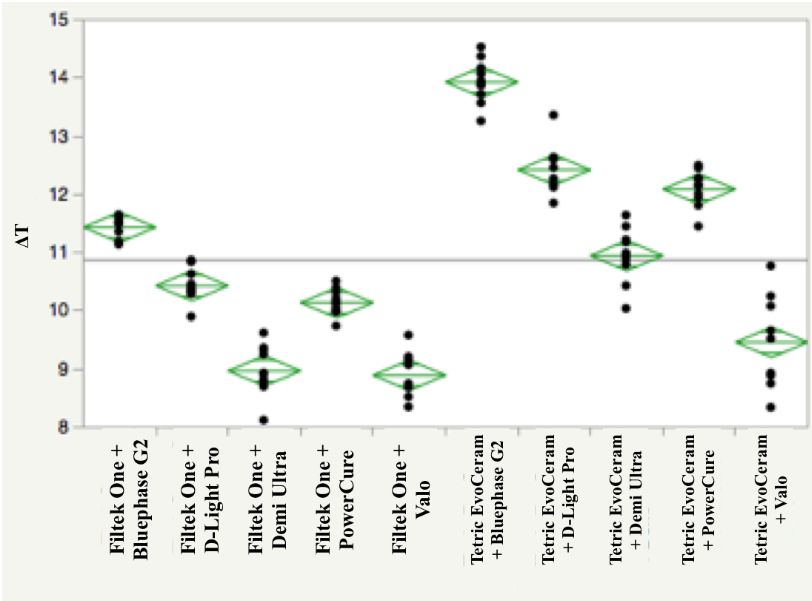

Figure 19: Group comparison for amount of temperature increase from baseline to the maximum temperature (ΔT). Groups which do not overlap in the green diamonds are significantly different

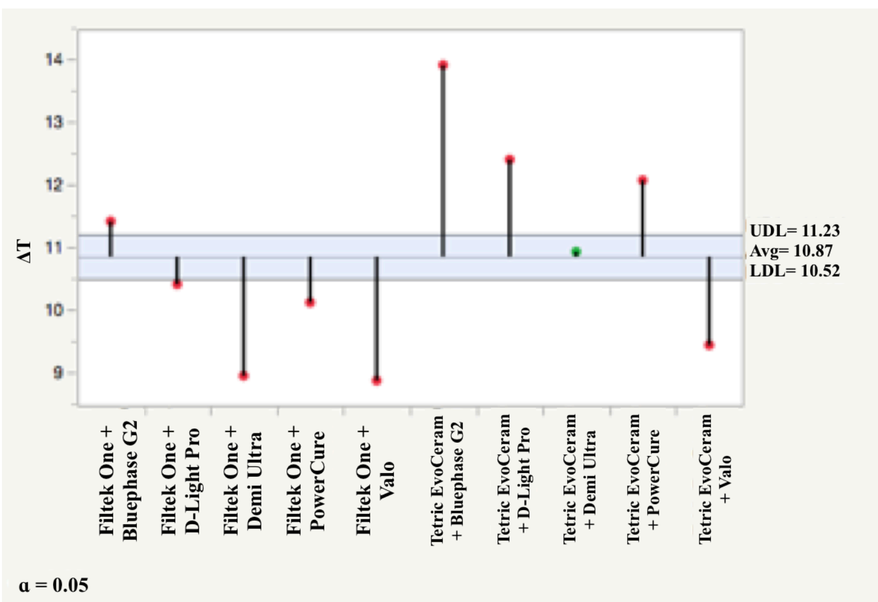

Figure 20 : Comparison against the overall mean

Table 5: Descriptive statistics for the amount of temperature increase from baseline to the maximum temperature (ΔT)

RBCs/LCU combination	n	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
FOB + Bluephase G2	10	11.44	0.18	0.06	11.31	11.56
FOB + D-Light Pro	10	10.43	0.28	0.09	10.23	10.64
FOB + Demi Ultra	10	8.97	0.43	0.14	8.66	9.28
FOB + Bluephase PowerCure	10	10.14	0.23	0.07	9.98	10.30
FOB + Valo Cordless	10	8.90	0.40	0.13	8.61	9.18
TEB + Bluephase G2	10	13.93	0.37	0.12	13.66	14.20
TEB + D-Light Pro	10	12.42	0.42	0.13	12.12	12.72
TEB + Demi Ultra	10	10.95	0.47	0.15	10.61	11.29
TEB + Bluephase PowerCure	10	12.09	0.31	0.10	11.87	12.32
TEB + Valo Cordless	10	9.46	0.76	0.24	8.92	10.00
FOB, Filtek One Bulk Fill Restorative; TEB, Tetric EvoCeram Bulk Fill						

3.2 Analysis of the Time to Reach Maximum Temperature on the Pulpal Wall (t)

For the both Filtek One Bulk Fill and Tetric EvoCeram Bulk Fill RBCs groups, there was no statistically significant difference between different LCU as determined by one-way ANOVA ($F(9,90) = 0.83$, $p=0.590$) (Figure 21), (Figure 22) and (Table 6).

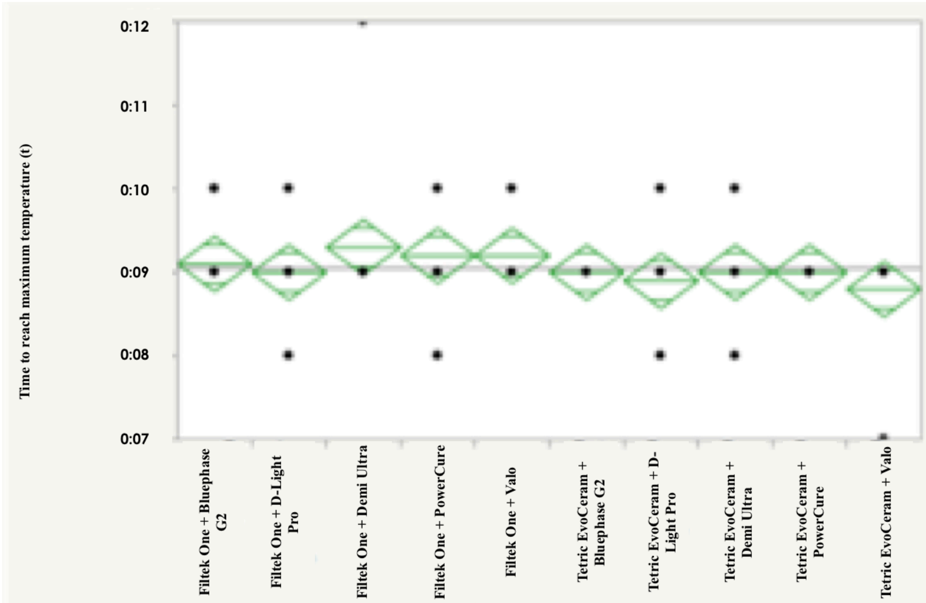

Figure 21: Group comparison for the time to reach maximum temperature on the pulpal wall (t). Groups which do not overlap in the green diamonds are significantly different

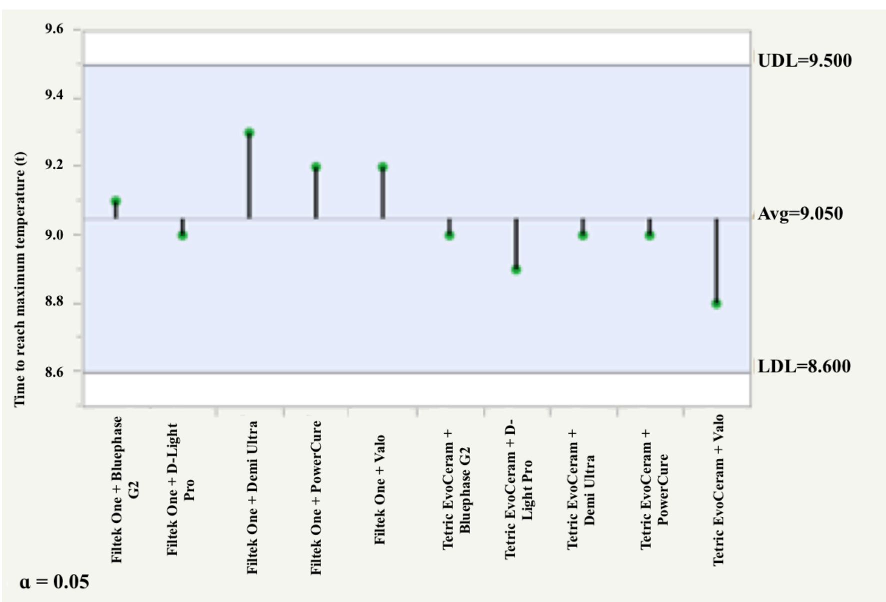

Figure 22: Comparison against the overall mean

Table 6: Descriptive statistics for the time to reach maximum temperature on the pulpal wall (t)

RBCs/LCU combination	n	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
FOB + Bluephase G2	10	9.10	0.32	0.10	8.87	9.33
FOB + D-Light Pro	10	9.00	0.47	0.15	8.66	9.34
FOB + Demi Ultra	10	9.30	0.95	0.30	8.62	9.98
FOB + Bluephase PowerCure	10	9.20	0.63	0.20	8.75	9.65
FOB + Valo Cordless	10	9.20	0.42	0.13	8.90	9.50
TEB + Bluephase G2	10	9.00	0.00	0.00	9.00	9.00
TEB + D-Light Pro	10	8.90	0.57	0.18	8.49	9.31
TEB + Demi Ultra	10	9.00	0.47	0.15	8.66	9.34
TEB + Bluephase PowerCure	10	9.00	0.00	0.00	9.00	9.00
TEB + Valo Cordless	10	8.80	0.63	0.20	8.35	9.25
FOB, Filtek One Bulk Fill Restorative; TEB, Tetric EvoCeram Bulk Fill						

3.3 Analysis of the Duration of the Temperature Above the Threshold (Δt)

A one-way ANOVA was conducted to determine if the duration of the temperature above the threshold was different by the five LCUs and the two RBCs. A significant statistical difference was noted between the groups as determined by one-way ANOVA ($F(9,90)=86.8$, $p < 0.001$).

Among the Filtek One Bulk Fill RBC groups, Tukey's post-hoc test revealed that multipeak Bluephase G2 LCU (24.00 ± 1.05 seconds) has a statistically significant longest duration of temperature above the threshold. The multipeak Valo Cordless LCU (15.80 ± 1.40 seconds) had a statistically significant shortest duration compared with the other LCUs except for the single peak Demi Ultra LCU (16.30 ± 1.49 seconds).

Among the Tetric EvoCeram Bulk Fill RBC groups, Tukey's post-hoc test revealed that the multipeak Valo Cordless LCU (17.80 ± 2.20 seconds) has a statistically significant

shortest duration of temperature above the threshold. On the other hand, the multipeak Bluephase G2 LCU (28.40 ± 1.65 seconds) had a statistically significant longest duration of temperature above the threshold. There was no statistical difference between Bluephase PowerCure LCU and D-Light Pro LCU, and between D-Light Pro LCU and Demi Ultra LCU (Figure 23) and (Figure 24)

Additionally, Tetric EvoCeram Bulk Fill RBC groups exhibited a statistically significant longer duration of temperature above the threshold than Filtek One Bulk Fill RBC when photopolymerized by Bluephase G2, Bluephase PowerCure, D-Light Pro and Demi Ultra. However, there was no statistical difference between the two RBCs when photopolymerized by Valo Cordless LCU (Table 7).

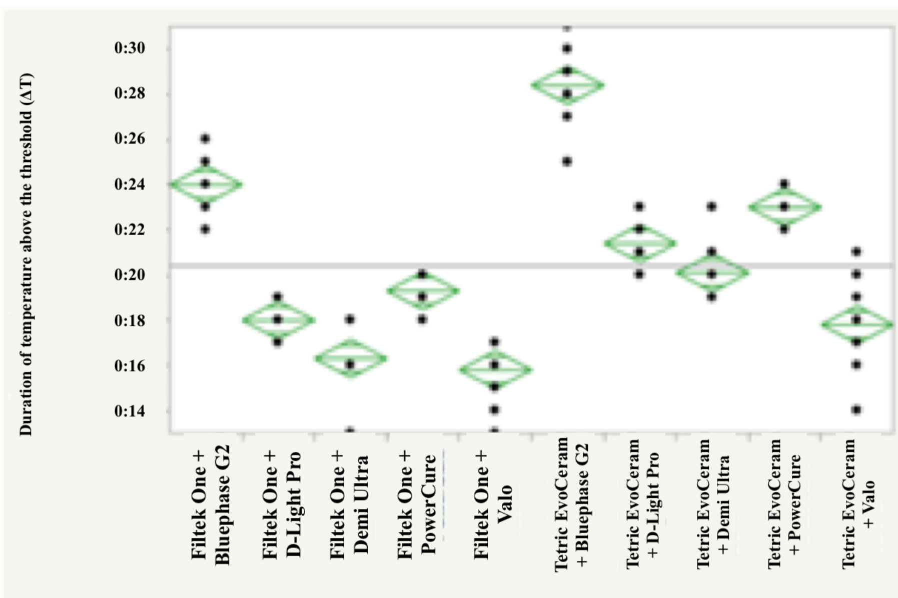

Figure 23: Group comparison for the duration of tempertature above the threshold (Δt). Groups which do not overlap in the green diamonds are significantly different

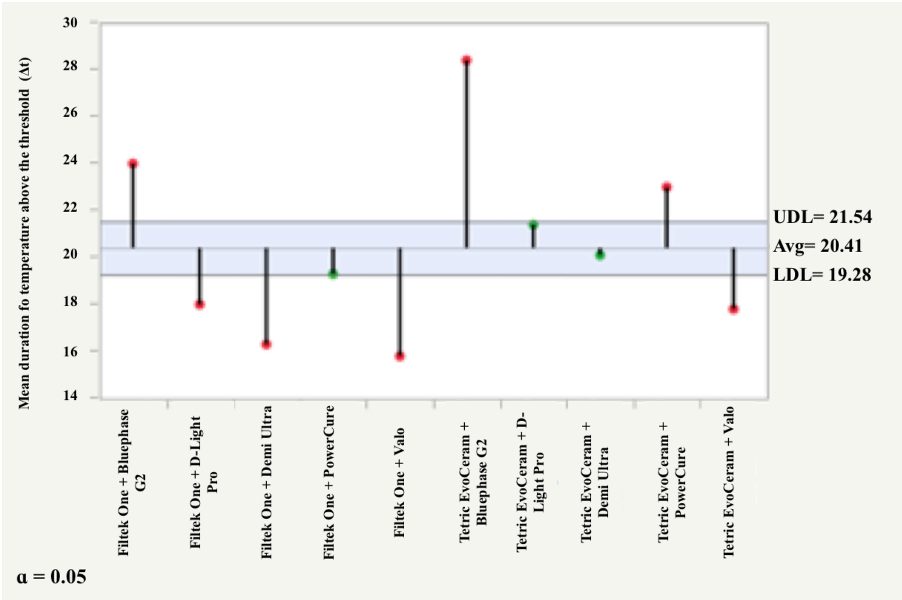

Figure 24: Comparison against the overall mean

Table 7: Descriptive statistics for the duration of the temperature above the threshold (Δt)

RBCs/LCU combination	n	Mean	Std Dev	Lower 95%	Upper 95%
FOB + Bluephase G2	10	24.00	1.05	23.25	24.75
FOB + D-Light Pro	10	18.00	0.82	17.42	18.58
FOB + Demi Ultra	10	16.30	1.49	15.23	17.37
FOB + Bluephase PowerCure	10	19.30	0.67	18.82	19.78
FOB + Valo Cordless	10	15.80	1.40	14.80	16.80
TEB + Bluephase G2	10	28.40	1.65	27.22	29.58
TEB + D-Light Pro	10	21.40	1.07	20.63	22.17
TEB + Demi Ultra	10	20.10	1.29	19.18	21.02
TEB + Bluephase PowerCure	10	23.00	0.82	22.42	23.58
TEB + Valo Cordless	10	17.80	2.20	16.23	19.37
FOB, Filtek One Bulk Fill Restorative; TEB, Tetric EvoCeram Bulk Fill					

3.4 Analysis of Heat Transmission Rate to the Pulpal Wall (Q)

A one-way ANOVA was conducted to determine if there is a significant difference of heat transfer rate between the five LED LCUs for each RBC used.

When comparing Filtek One Bulk Fill RBC photopolymerized by the different LED LCUs, there was a significant difference using one-way ANOVA ($F(4,45) = 14.45$, $p < 0.001$). As determined by using Tukey Honestly Significant Difference (HSD), Valo Cordless (0.06 ± 0.01 Watts) transferred significantly lower heat than other LCUs, while Bluephase PowerCure (0.11 ± 0.01 Watts) transferred significantly higher heat than Demi Ultra and D-Light Pro (Figure 25). Descriptive statistics and Tukey HSD Comparison are illustrated in (Table 8) and (Table 9).

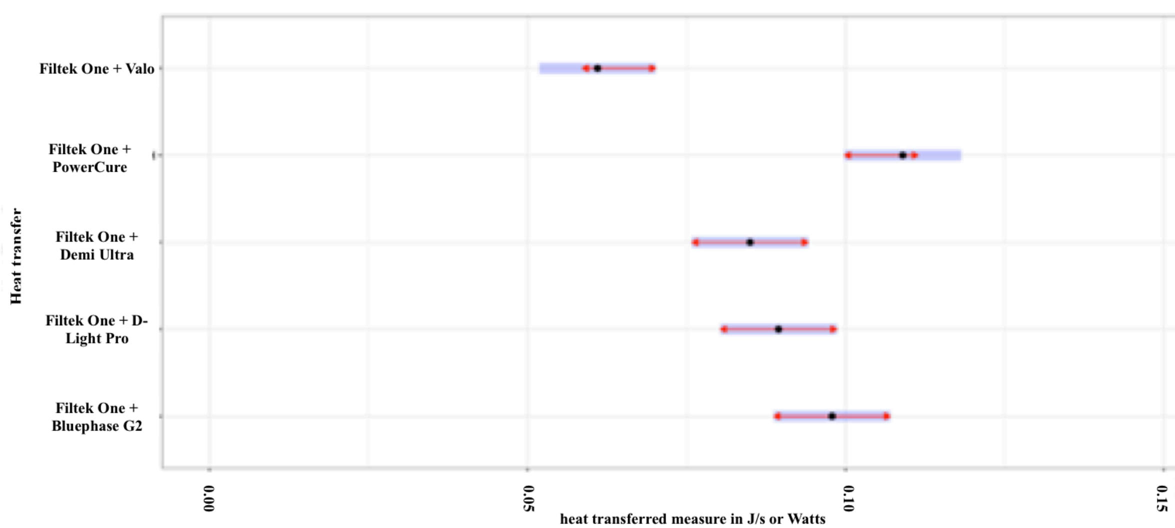

Figure 25: Means plot for the heat transfer rate of Filtek One Bulk-Fill RBC photopolymerized by different LCUs. The blue bars are Confidence intervals for the means, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow from another group, the difference is not significant

Table 8: Descriptive statistics for the heat transfer rate of Filtek One Bulk Fill RBC photopolymerized by different LCUs

Group	N	Mean	SD	Min	Max
FOB + Bluephase G2	10	0.10	0.02	0.06	0.13
FOB + D-Light Pro	10	0.09	0.01	0.08	0.10
FOB + Demi	10	0.09	0.02	0.05	0.11
FOB + Bluephase PowerCure	10	0.11	0.01	0.09	0.12
FOB + Valo Cordless	10	0.06	0.01	0.05	0.08
FOB, Filtek One Bulk Fill Restorative					

Table 9: Tukey HSD Comparison of different LCU photopolymerize Filtek One Bulk Fill RBC

LCU Comparison	Difference	Lower 95% CI	Upper 95% CI	P-Value
Bluephase G2 – D-Light Pro	0.01	-0.000	0.02	0.688
Bluephase G2 – Demi Ultra	0.01	0.00	0.03	0.281
Bluephase G2 – Bluephase PowerCure	-0.01	-0.02	0.00	0.427
Bluephase G2 – Valo Cordless	0.04	0.02	0.05	<.0001
D-Light Pro – Demi Ultra	0.00	-0.01	0.02	0.956
D-Light Pro – Bluephase PowerCure	-0.02	-0.03	-0.01	0.031
D-Light Pro – Valo Cordless	0.03	0.02	0.04	0.001
Demi Ultra – Bluephase PowerCure	-0.02	-0.04	-0.01	0.005
Demi Ultra – Valo Cordless	0.02	0.01	0.04	0.005
Bluephase PowerCure – Valo Cordless	0.05	0.04	0.06	<.0001

When comparing Tetric EvoCeram Bulk Fill RBC photopolymerized by the different LED LCUs, there was a significant difference using one-way ANOVA ($F(4,45) = 14.58$, $p < 0.001$). As determined by using Tukey Honestly Significant Difference (HSD), Demi Ultra

LCU (0.10 ± 0.01 Watts) transferred significantly lower heat than Valo Cordless, Bluephase PowerCure, and D-Light Pro, but was not significantly lower than Bluephase G2. (Figure 26). Descriptive statistics and Tukey HSD Comparison are illustrated in (Table 10) and (Table 11).

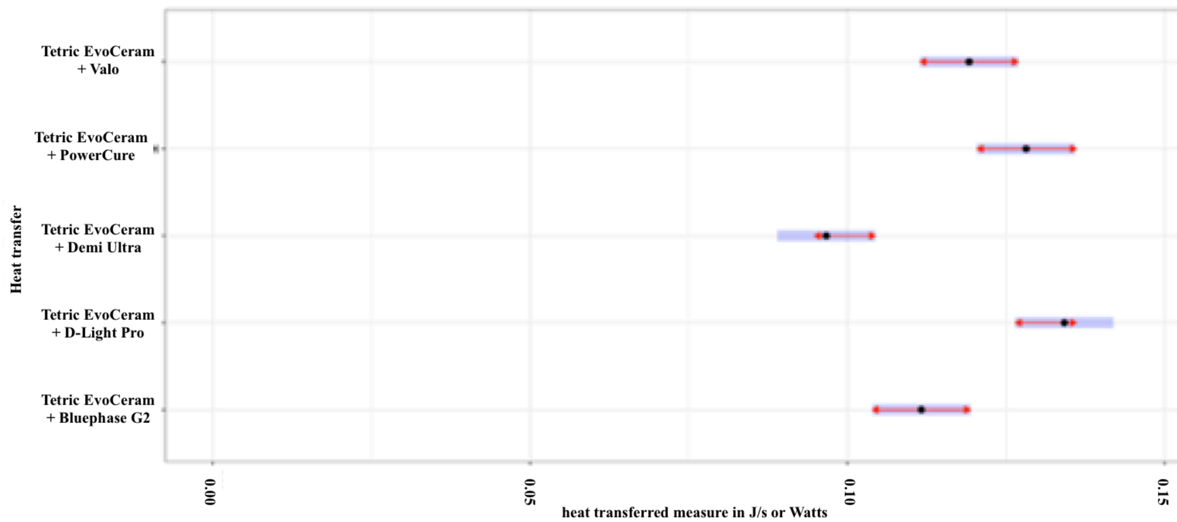

Figure 26: Means plot for the heat transfer rate of Tetric EvoCeram Bulk Fill RBC photopolymerized by different LCUs. The blue bars are Confidence intervals for the means, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow

Table 10: Descriptive statistics for the heat transfer rate of Tetric EvoCeram Bulk Fill RBC photopolymerized by different LCUs

Group	N	Mean	SD	Min	Max
TEB + Bluephase G2	10	0.11	0.01	0.09	0.12
TEB + D-Light Pro	10	0.13	0.01	0.10	0.15
TEB + Demi	10	0.10	0.01	0.07	0.12
TEB + Bluephase PowerCure	10	0.13	0.01	0.10	0.15
TEB + Valo Cordless	10	0.12	0.01	0.11	0.14
TEB, Tetric EvoCeram Bulk Fill					

Table 11: Tukey HSD Comparison of different LCU photopolymerize Tetric EvoCeram Bulk Fill RBC

LCU Comparison	Difference	Lower 95% CI	Upper 95% CI	P-Value
Bluephase G2 – D-Light Pro	-0.02	-0.03	-0.01	0.001
Bluephase G2 – Demi Ultra	0.01	0.00	0.03	0.061
Bluephase G2 – Bluephase PowerCure	-0.02	-0.03	-0.01	0.031
Bluephase G2 – Valo Cordless	-0.01	-0.02	0.00	0.641
D-Light Pro – Demi Ultra	0.04	0.03	0.05	<.0001
D-Light Pro – Bluephase PowerCure	0.01	-0.00	0.02	0.801
D-Light Pro – Valo Cordless	0.02	0.00	0.03	0.060
Demi Ultra – Bluephase PowerCure	-0.03	-0.04	-0.02	<.0001
Demi Ultra – Valo Cordless	-0.02	-0.03	-0.01	0.001
Bluephase PowerCure – Valo Cordless	0.01	-0.00	0.02	0.472

CHAPTER 4: DISCUSSION

The use of LED LCUs to photopolymerize RBCs generated an increase in the temperature of the axial pulpal wall. Zach & Cohen reported an increase of 5.5°C within the pulp chamber caused irreversible pulp damage in 15% of the subjects.[10] This value has been considered as a safe threshold in many heat-generation studies, and it has been advised to keep the temperature change below 5.5°C. In this study, we analyzed the heat generation profile on the axial pulpal wall of an extracted human tooth using two commercially available bulk-fill RBC, cured with multipeak and single peak commercially available LED LCUs. Several conditions are different in the in-vivo situation compared to this experimental setup. For instance, the baseline temperature in healthy and normal tooth pulp is approximately 35°C[57,58] compared to 21°C in the current setting. Also, the temperature was measured on the pulpal wall, and that does not necessarily mean a change of the temperature of the actual pulpal tissue, which is located deeper.

Additionally, the presence of blood circulation, pulpal soft tissue, the periodontal ligament can help in dissipating the heat generated on the pulp tissue.[8,59] However, conducting the experiments under controlled conditions help comparing the different LCUs and RBCs in relation to each other, keeping in mind the value of temperature will be different in *in-vivo* situations. Furthermore, the use of a single tooth model without etching or using a bonding agent allows the removal of the RBCs without damaging the tooth. At the same time, this approach ensures the standardization of the measurements. This approach is supported by Hannig et al.,[55] who found no significant difference in heat temperature measurement with and without applying a bonding agent before polymerization of composite resins.

Many factors can influence the heat generation on the pulpal wall, including the amount of remaining dentin thickness, LCU intensity, duration of curing, and type of composite material used.[53,60,61] It has been reported that the influence of intensity of the light emitted by LCU and the exposure time on the heat generation is greater and of prime importance than the exothermic reaction of composite and the remaining dentin thickness.[62] However, the presence of a thin dentin layer and higher exothermic reaction can contribute to the increase of pulpal temperature[60,62]. The choice of 0.5 mm remaining dentin thickness in the current study was to accentuate the effect of heat from the LCUs and RBCs, and to mimic the extreme situation in the clinical setting such as deep cavity preparations.

Our study shows that different composites can heat up differently using the same LCU on the same radiant emittance output. Tetric EvoCeram Bulk Fill exhibited significantly higher temperature rise (ΔT) on the pulpal wall than Filtek One Bulk Fill when photopolymerized with the same LCUs, except for Valo Cordless groups where there was no statistical difference.

It was assumed that the presence of a violet LED chip in the multipeak LCU, which has a lower wavelength and, consequently, higher energy, can contribute to the increase of the energy delivered and, in turn, the rise in pulpal temperature. This assumption was in accordance with our findings for most of the LCUs tested in the study, with the exception of Valo cordless. The single peak LCU Demi Ultra and the multipeak Valo Cordless scored significantly lower temperature rise when used with Filtek One Bulk Fill RBC. Among the Tetric EvoCeram Bulk Fill RBC groups, Valo Cordless had a statistically significant lowest value in the amount of pulpal temperature rise followed by Demi Ultra. Even though the measured radiant emittance for both of them (Valo Cordless and Demi Ultra) were among the

highest measured in the study (Table 4), and additionally, Demi Ultra is a pulsated LCU, and that may contribute the lower value for temperature rise.

All specimens in our study were photopolymerized according to the manufacturer's instructions for 10 seconds for up to 3 mm depth on radiant emittance of more than 1,000 mW/cm^2. This photopolymerization time is a substantial decrease compared to the previous most commonly used QTH LCUs, which required about 30-60 seconds of exposure. The shorter photopolymerization time is desirable by many practitioners to achieve faster procedures and decrease the time of radiant emittance, which may help to decrease the temperature rise on the pulp wall as well. In our experiment, some specimens sustain a higher temperature for a longer time on the pulpal wall than the others. The longer the exposure to a higher temperature carries an increased risk of pulpal injury. For both RBCs used in the study, Bluephase G2 LCU had a statistically significant longer duration above the threshold (24.0 ± 1.05 seconds) for Filtek One Bulk Fill group and (28.4 ±1.65 seconds) for Tetric EvoCeram Bulk Fill group. The multipeak Valo Cordless LCU (17.80 ± 2.20 seconds) had a statistically significant shorter duration above the threshold than all other LCUs for Tetric EvoCeram group. While with Filtek One Bulk Fill, Valo Cordless LCU (15.80 ± 1.40 seconds) had a statistically significant shorter duration than all other LCUs except for Demi Ultra LCU.

Our study also showed that different RBCs could heat up differently when photopolymerized with the same LCU. Filtek One Bulk Fill had a statistically significant lower amount of heat generation, and shorter duration of temperature above the threshold when it was photopolymerized with multipeak Bluephase G2, Bluephase PowerCure, D-Light Pro and the single peak Demi Ultra. However, there was no statistical difference between RBCs when photopolymerized by Valo Cordless LCU.

One explanation for the difference in the amount of heat produced and sustained could be attributed to the different filler content and type of monomer used. It has been reported that the increase of filler loading (%) associated with a decrease in heat produced by RBC when photopolymerized.[48,63] The reason is that heat is produced when (C=C) double bonds convert to (C–C) single bond in methacrylate monomers, and composites with more matrix and less filler content are expected to generate more heat. In our study Tetric EvoCeram Bulk Fill (76-77wt%, 53-54vol%) has lower filler content than Filtek One Bulk Fill (76.5wt%, 58.4vol%), hence it is expected to produce more heat.

To verify the adequate polymerization of both RBCs and to try to relate to why one was heating more than the other, a pilot study was conducted to obtain Vickers hardness Numbers (VHN) for RBCs used in the study. A 3D model with a mold measured (4mm width, 2mm length, 10mm depth) was designed, and 3D printed. The mold was packed with RBCs, covered with Mylar strip, and photopolymerized for 10 seconds. This process was repeated for each LCU/RBC combination. Each specimen was sectioned longitudinally at the center of the photopolymerized RBC using slow speed saw (Buehler Isomet LS Precision Saw, Lake Bluff, IL USA, with a diamond disk, Isomet Blade 15HC, 4in). The surface of the exposed composite was finished and polished using 600, 800, then 1200-grits SiC paper. VHN was measured as a function of depth of the material at 0.1 mm from the surface in the center of the photopolymerized RBC, then at 0.5 mm increments for 4.1 mm depth using a fixed load of 200 g with a dwell time of 15 seconds. The initial results show that there was a trend for Filtek One Bulk Fill to be of higher VHN than Tetric EvoCeram Bulk Fill when they were photopolymerized with the same LCU. However, more samples would be required to make an accurate statement.

The use of the thermal infrared camera and the minimal-energy-loss mirror allowed direct and indirect visualization of the pulpal wall and RBCs temperature simultaneously. This allowed the application of the 1-Dimensional Thermal Equation to measure heat transmission or heat flux (Watts or J/s). The results of the study showed that when using Filtek One Bulk Fill, Valo Cordless (0.06 ± 0.1 Watts) had statistically significant lower rate of heat transfer than the other LCU, while Bluephase PowerCure (0.11 ± 0.1 Watts) was significantly higher than Demi Ultra (0.09 ± 0.2 Watts), and D-Light Pro (0.09 ± 0.1 Watts). When using Tetric EvoCeram Bulk Fill, Demi Ultra (0.10 ± 0.1 Watts) had a statistically significant lower rate of heat transfer than the other LCUs.

CHAPTER 5: CONCLUSION

All of the three hypotheses of the study had to be, in most part, rejected. There was a difference between the different LCUs with respect to the heat transmitted and generated, but not necessary between multipeak and single peak, even though the majority of the multipeak LCU had a higher rate of heat transmission and generation. In conclusion, some multipeak LCUs can produce more heat generation and impose an additional risk of pulp injury. Different bulk-fill RBCs can heat up differently and consequently can cause an additional risk of pulp injury. Further in-vivo studies are needed to accurately identify the in situ thermal behaviors of the RBCs and LCUs.

APPENDIX: Raw Data

1- Raw Data of Tetric EvoCeram Bulk Fill (TEB):

Sample	Duration of the temp. above the threshold (Δt)	Time to reach maximum temperature (t)	Amount of temperature increase from baseline to maximum temperature (ΔT)	Max. temp on the Composite (T_1)	Max. temp on the Pulp Wall (T_2)	Difference (T_1-T_2)	Heat transfer (Q) (Joules/ sec)
TEB + Bluephase PowerCure 01	24s	9s	12.5	45.23	31.54	13.69	0.133
TEB + Bluephase PowerCure 02	22s	10s	11.4	43.65	30.80	12.85	0.125
TEB + Bluephase PowerCure 03	23s	9s	12.2	44.72	31.11	13.61	0.132
TEB + Bluephase PowerCure 04	24s	9s	12.1	44.16	31.81	12.35	0.120
TEB + Bluephase PowerCure 05	25s	9s	12.4	43.59	33.06	10.53	0.102
TEB + Bluephase PowerCure 06	24s	9s	12.3	45.06	32.49	12.57	0.122
TEB + Bluephase PowerCure 07	23s	9s	12.3	44.43	32.33	12.1	0.118
TEB + Bluephase PowerCure H 08	24s	10s	11.8	45.93	31.93	14	0.136
TEB + Bluephase PowerCure 09	24s	9s	12.0	45.69	31.34	14.35	0.139
TEB + Bluephase PowerCure 10	24s	10s	11.9	48.20	32.33	15.87	0.154
TEB + Bluephase G2 01	29s	10s	13.6	44.08	32.72	11.36	0.110
TEB + Bluephase G2 02	29s	10s	13.9	44.80	34.05	10.75	0.104
TEB + Bluephase G2 03	25s	10s	13.3	44.08	32.27	11.81	0.115
TEB + Bluephase G2 04	31s	9s	13.9	46.47	33.61	12.86	0.125
TEB + Bluephase G2 05	28s	10s	14.1	44.76	33.26	11.5	0.112
TEB + Bluephase G2 06	28s	10s	14.4	45.77	33.60	12.17	0.118

TEB + Bluephase G2 07	29s	9s	14.2	44.67	33.94	10.73	0.104
TEB + Bluephase G2 08	30s	10s	14.5	43.65	34.21	9.44	0.092
TEB + Bluephase G2 09	29s	10s	13.7	45.50	33.48	12.02	0.117
TEB + Bluephase G2 10	29s	9s	13.9	45.26	32.97	12.29	0.119
TEB + Valo Cordless 01	17s	10s	8.7	38.95	28.07	10.88	0.106
TEB + Valo Cordless 02	17s	9s	8.9	40.75	28.11	12.64	0.123
TEB + Valo Cordless 03	18s	10s	9.5	40.69	29.17	11.52	0.112
TEB + Valo Cordless 04	17s	9s	8.9	41.56	27.59	13.97	0.136
TEB + Valo Cordless 05	20s	10s	10.2	41.58	28.72	12.86	0.125
TEB + Valo Cordless 06	18s	10s	9.5	40.89	29.49	11.4	0.111
TEB + Valo Cordless 07	19s	10s	10.1	41.34	28.61	12.73	0.124
TEB + Valo Cordless 08	21s	10s	9.7	41.75	28.07	13.68	0.133
TEB + Valo Cordless 09	21s	10s	10.8	40.09	28.13	11.96	0.116
TEB + Valo Cordless 10	14s	7s	8.3	37.88	26.85	11.03	0.107
TEB + Demi Ultra 01	21s	9s	11.4	38.89	30.14	8.75	0.085
TEB + Demi Ultra 02	19s	10s	10.0	40.01	30.12	9.89	0.096
TEB + Demi Ultra 03	20s	10s	11.0	41.25	31.02	10.23	0.099
TEB + Demi Ultra 04	21s	9s	11.2	41.40	31.86	9.54	0.093
TEB + Demi Ultra 05	21s	10s	11.0	40.19	30.96	9.23	0.090
TEB + Demi Ultra 06	23s	9s	11.6	38.72	31.72	7	0.068
TEB + Demi Ultra 07	21s	8s	11.2	41.77	31.20	10.57	0.103
TEB + Demi Ultra 08	20s	10s	10.9	41.53	30.55	10.98	0.107
TEB + Demi Ultra 09	19s	10s	10.8	42.40	30.44	11.96	0.116
TEB + Demi Ultra 10	19s	10s	10.4	41.33	29.96	11.37	0.110
TEB + D-Light Pro 01	23s	11s	13.4	45.51	31.90	13.61	0.132
TEB + D-Light Pro 02	23s	10s	12.6	41.87	31.09	10.78	0.105
TEB + D-Light Pro 03	21s	9s	12.1	46.20	31.29	14.91	0.145
TEB + D-Light Pro 04	22s	10s	12.3	44.54	31.07	13.47	0.131
TEB + D-Light Pro 05	22s	10s	12.6	45.95	31.52	14.43	0.140

TEB + D-Light Pro 06	20s	9s	12.5	44.75	30.55	14.2	0.138
TEB + D-Light Pro 07	21s	9s	12.2	44.85	30.93	13.92	0.135
TEB + D-Light Pro 08	23s	10s	11.8	44.04	30.84	13.2	0.128
TEB + D-Light Pro 09	21s	9s	12.2	45.41	30.98	14.43	0.140
TEB + D-Light Pro 10	23s	9s	12.6	47.16	31.99	15.17	0.147

2- Raw Data of Filtek One Bulk Fill Restorative (FOB):

Sample	Duration of the temp. above the threshold (Δt)	Time to reach maximum temperature (t)	Amount of temperature increase from baseline to maximum temperature (ΔT)	Max. temp on the Composite (T_1)	Max. temp on the Pulp Wall (T_2)	Difference (T_1-T_2)	Heat transfer (Q) (Joules/ sec)
FOB + Bluephase PowerCure 01	19s	8s	10.04	40.30	30.55	9.75	0.095
FOB + Bluephase PowerCure 02	20s	10s	10.39	41.32	30.48	10.84	0.105
FOB + Bluephase PowerCure 03	20s	10s	10.50	42.50	30.84	11.66	0.113
FOB + Bluephase PowerCure 04	20s	10s	10.21	42.36	30.73	11.63	0.113
FOB + Bluephase PowerCure 05	21s	10s	10.31	40.97	31.09	9.88	0.096
FOB + Bluephase PowerCure 06	20s	10s	9.99	41.88	30.46	11.42	0.111
FOB + Bluephase PowerCure 07	19s	10s	10.15	42.40	30.78	11.62	0.113
FOB + Bluephase PowerCure H 08	19s	10s	9.73	41.07	29.83	11.24	0.109
FOB + Bluephase PowerCure 09	21s	10s	9.97	43.31	31.00	12.31	0.120
FOB + Bluephase PowerCure 10	20s	10s	10.11	42.64	30.80	11.84	0.115
FOB + Bluephase G2 01	23s	9s	11.53	39.31	32.87	6.44	0.063
FOB + Bluephase G2 02	25s	10s	11.64	42.00	31.63	10.37	0.101
FOB + Bluephase G2 03	26s	9s	11.60	43.44	32.33	11.11	0.108
FOB + Bluephase G2 04	24s	10s	11.18	41.98	31.72	10.26	0.100
FOB + Bluephase G2 05	23s	9s	11.36	41.21	31.23	9.98	0.097
FOB + Bluephase G2 06	26s	10s	11.50	42.28	33.73	8.55	0.083
FOB + Bluephase G2 07	25s	10s	11.59	41.68	31.54	10.14	0.099

FOB + Bluephase G2 08	25s	10s	11.35	44.78	30.91	13.87	0.135
FOB + Bluephase G2 09	24s	10s	11.48	41.01	32.18	8.83	0.086
FOB + Bluephase G2 10	25s	10s	11.13	42.59	31.39	11.2	0.109
FOB + Valo Cordless 01	17s	10s	9.06	36.73	30.69	6.04	0.059
FOB + Valo Cordless 02	18s	10s	9.57	37.19	30.69	6.5	0.063
FOB + Valo Cordless 03	14s	10s	8.34	35.35	29.40	5.95	0.058
FOB + Valo Cordless 04	17s	10s	9.21	36.60	30.84	5.76	0.056
FOB + Valo Cordless 05	17s	9s	8.74	36.61	30.44	6.17	0.060
FOB + Valo Cordless 06	17s	10s	9.20	36.32	30.44	5.88	0.057
FOB + Valo Cordless 07	17s	10s	8.67	36.41	29.49	6.92	0.067
FOB + Valo Cordless 08	16s	10s	8.51	35.91	29.87	6.04	0.059
FOB + Valo Cordless 09	15s	10s	8.51	35.70	30.48	5.22	0.051
FOB + Valo Cordless 10	17s	10s	9.14	37.61	29.29	8.32	0.081
FOB + Demi Ultra 01	17s	10s	8.80	38.98	29.99	8.99	0.087
FOB + Demi Ultra 02	17s	9s	8.69	41.64	29.90	11.74	0.114
FOB + Demi Ultra 03	18s	13s	9.61	39.13	29.69	9.44	0.092
FOB + Demi Ultra 04	16s	10s	8.92	39.54	30.37	9.17	0.089
FOB + Demi Ultra 05	18s	9s	9.35	39.17	31.45	7.72	0.075
FOB + Demi Ultra 06	17s	9s	8.90	37.27	30.91	6.36	0.062
FOB + Demi Ultra 07	19s	10s	9.24	41.17	29.42	11.75	0.114
FOB + Demi Ultra 08	17s	9s	9.33	36.99	30.98	6.01	0.058
FOB + Demi Ultra 09	14s	10s	8.11	36.08	30.59	5.49	0.053
FOB + Demi Ultra 10	17s	10s	8.75	40.62	29.80	10.82	0.105
FOB + D-Light Pro 01	18s	10s	9.89	38.86	29.56	9.3	0.090
FOB + D-Light Pro 02	19s	10s	10.83	40.47	31.09	9.38	0.091
FOB + D-Light Pro 03	20s	9s	10.28	40.25	30.69	9.56	0.093
FOB + D-Light Pro 04	18s	8s	10.86	39.51	31.16	8.35	0.081
FOB + D-Light Pro 05	18s	9s	10.62	39.25	30.32	8.93	0.087
FOB + D-Light Pro 06	19s	10s	10.35	40.01	30.46	9.55	0.093
FOB + D-Light Pro 07	18s	10s	10.32	39.95	30.21	9.74	0.095

FOB + D-Light Pro 08	19s	10s	10.40	38.89	30.50	8.39	0.082
FOB + D-Light Pro 09	18s	9s	10.32	38.78	30.30	8.48	0.082
FOB + D-Light Pro 10	19s	9s	10.45	40.38	29.96	10.42	0.101

CHAPTER 6: BIBLIOGRAPHY

1. Kilinc E, Roshkind DM, Antonson SA, et al. Thermal safety of Er:YAG and Er,Cr:YSGG lasers in hard tissue removal. *Photomed Laser Surg.* 2009;27(4):565-570.

2. Cavalcanti BN, Lage-Marques JL, Rode SM. Pulpal temperature increases with Er:YAG laser and high-speed handpieces. *J Prosthet Dent.* 2003;90(5):447-451.

3. Tjan AH, Grant BE, Godfrey MF, 3rd. Temperature rise in the pulp chamber during fabrication of provisional crowns. *J Prosthet Dent.* 1989;62(6):622-626.

4. Khajuria RR, Madan R, Agarwal S, Gupta R, Vadavadgi SV, Sharma V. Comparison of temperature rise in pulp chamber during polymerization of materials used for direct fabrication of provisional restorations: An in-vitro study. *Eur J Dent.* 2015;9(2):194-200.

5. Michalakis K, Pissiotis A, Hirayama H, Kang K, Kafantaris N. Comparison of temperature increase in the pulp chamber during the polymerization of materials used for the direct fabrication of provisional restorations. *J Prosthet Dent.* 2006;96(6):418-423.

6. Eldeniz AU, Usumez A, Usumez S, Ozturk N. Pulpal temperature rise during light-activated bleaching. *J Biomed Mater Res B Appl Biomater.* 2005;72(2):254-259.

7. Sulieman M, Rees JS, Addy M. Surface and pulp chamber temperature rises during tooth bleaching using a diode laser: a study in vitro. *Br Dent J.* 2006;200(11):631-634; discussion 619.

8. Braga S, Oliveira L, Ribeiro M, et al. Effect of Simulated Pulpal Microcirculation on Temperature When Light Curing Bulk Fill Composites. *Oper Dent.* 2019;44(3):289-301.

9. 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(4):298-306.

10. Zach L, Cohen G. Pulp Response to Externally Applied Heat. *Oral Surg Oral Med Oral Pathol.* 1965;19:515-530.

11. Lynch CD, Roberts JL, Al-Shehri A, Milward PJ, Sloan AJ. An ex-vivo model to determine dental pulp responses to heat and light-curing of dental restorative materials. *J Dent.* 2018;79:11-18.

12. 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(11):791-801.

13. Asmussen E, Peutzfeldt A. Temperature rise induced by some light emitting diode and quartz-tungsten-halogen curing units. *Eur J Oral Sci.* 2005;113(1):96-98.

14. Mouhat M, Mercer J, Stangvaltaite L, Ortengren U. Light-curing units used in dentistry: factors associated with heat development-potential risk for patients. *Clin Oral Investig.* 2017;21(5):1687-1696.

15. Buonocore MG, Davila J. Restoration of fractured anterior teeth with ultraviolet-light-polymerized bonding materials: a new technique. *J Am Dent Assoc.* 1973;86(6):1349-1354.

16. Lienhard O, inventor. Canard Precision Industries, Inc., assignee: Instrument for transmitting ultraviolet radiation to a limited area. United States Patent 3,712,984. In:1973.

17. Rueggeberg F. Contemporary issues in photocuring. *Compend Contin Educ Dent Suppl.* 1999(25):S4-15; quiz S73.

18. Rueggeberg FA, Giannini M, Arrais CAG, Price RBT. Light curing in dentistry and clinical implications: a literature review. *Braz Oral Res.* 2017;31(suppl 1):e61.

19. Nakamura S, Mukai T, Iwasa N. Light-emitting gallium nitride-based compound semiconductor device. In: Google Patents; 1996.

20. Mills RW. Blue light emitting diodes--another method of light curing? *Br Dent J.* 1995;178(5):169.

21. Osterwalder JM, Creamer AA. Apparatus for curing resin in dentistry. In: United States Patent 6,102,696; 2000.

22. Kennedy J. Portable LED photocuring device. In: United States Patent 5,420,768; 1995.

23. Kennedy J, Kayser R. Portable light emitting apparatus with a semiconductor emitter array. In: United States Patent 5,634,711; 1997.

24. FUJIBAYASHI K, ISHIMARU K, TAKAHASHI N, KOHNO A. Newly developed curing unit using blue light-emitting diodes. *Dentistry in Japan.* 1998;34:49-53.

25. Mills RW, Jandt KD, Ashworth SH. Dental composite depth of cure with halogen and blue light emitting diode technology. *Br Dent J.* 1999;186(8):388-391.

26. Rueggeberg FA. State-of-the-art: dental photocuring--a review. *Dent Mater.* 2011;27(1):39-52.

27. Ikemura K, Endo T. A review of the development of radical photopolymerization initiators used for designing light-curing dental adhesives and resin composites. *Dent Mater J.* 2010;29(5):481-501.

28. Jandt KD, Mills RW. A brief history of LED photopolymerization. *Dent Mater.* 2013;29(6):605-617.

29. Shortall AC, Palin WM, Jacquot B, Pelissier B. Advances in light-curing units: four generations of LED lights and clinical implications for optimizing their use: Part 2. From present to future. *Dent Update.* 2012;39(1):13-17, 20-12.

30. Pelissier B, Jacquot B, Palin WM, Shortall AC. Three generations of LED lights and clinical implications for optimizing their use. 1: from past to present. *Dent Update.* 2011;38(10):660-662, 664-666, 668-670.

31. Cao D. Light for use in activating light-activated materials, the light having a plurality of light emitting semiconductor chips emitting light of differing peak wavelengths to provide a wide light spectrum profile. In: United States Patents 6,955,537; 2005.

32. Price RBT. Light Curing in Dentistry. *Dent Clin North Am.* 2017;61(4):751-778.

33. Dart EC, Nemcek J. Photopolymerisable composition. Great Britain Patent Specification. 1408265. (1971); Japanese Patent No. Toku-Kou-Sho 54-10986 (1979).

34. Brackett MG, Brackett WW, Browning WD, Rueggeberg FA. The effect of light curing source on the residual yellowing of resin composites. *Oper Dent.* 2007;32(5):443-450.

35. Park YJ, Chae KH, Rawls HR. Development of a new photoinitiation system for dental light-cure composite resins. *Dent Mater.* 1999;15(2):120-127.

36. de Oliveira D, Rocha MG, Correa IC, Correr AB, Ferracane JL, Sinhoreti MAC. The effect of combining photoinitiator systems on the color and curing profile of resin-based composites. *Dent Mater.* 2016;32(10):1209-1217.

37. Neumann MG, Schmitt CC, Ferreira GC, Correa IC. The initiating radical yields and the efficiency of polymerization for various dental photoinitiators excited by different light curing units. *Dent Mater.* 2006;22(6):576-584.

38. Schneider LF, Cavalcante LM, Consani S, Ferracane JL. Effect of co-initiator ratio on the polymer properties of experimental resin composites formulated with camphorquinone and phenyl-propanedione. *Dent Mater.* 2009;25(3):369-375.

39. Ivoclar V. Research and Development Report no. 19. *Schaan Liechtenstein.* 2013;44.

40. Zorzin J, Maier E, Harre S, et al. Bulk-fill resin composites: polymerization properties and extended light curing. *Dent Mater.* 2015;31(3):293-301.

41. 3M ESPE. Filtek One Bulk Fill Restorative. Technical Product Profile. *St Paul, MN, USA.* 2016;https://multimedia.3m.com/mws/media/1317671O/3m-filtek-one-bulk-fill-restorative-technical-product-profile.pdf(https://multimedia.3m.com/mws/media/1317671O/3m-filtek-one-bulk-fill-restorative-technical-product-profile.pdf).

42. Jang JH, Park SH, Hwang IN. Polymerization shrinkage and depth of cure of bulk-fill resin composites and highly filled flowable resin. *Oper Dent.* 2015;40(2):172-180.

43. Lassila LV, Nagas E, Vallittu PK, Garoushi S. Translucency of flowable bulk-filling composites of various thicknesses. *Chin J Dent Res.* 2012;15(1):31-35.

44. Van Ende A, De Munck J, Lise DP, Van Meerbeek B. Bulk-Fill Composites: A Review of the Current Literature. *J Adhes Dent.* 2017;19(2):95-109.

45. Lima RBW, Troconis CCM, Moreno MBP, Murillo-Gomez F, De Goes MF. Depth of cure of bulk fill resin composites: A systematic review. *J Esthet Restor Dent.* 2018;30(6):492-501.

46. Linsuwanont P, Palamara JE, Messer HH. Thermal transfer in extracted incisors during thermal pulp sensitivity testing. *Int Endod J.* 2008;41(3):204-210.

47. Jo SA, Lee CH, Kim MJ, Ferracane J, Lee IB. Effect of pulse-width-modulated LED light on the temperature change of composite in tooth cavities. *Dent Mater.* 2019;35(4):554-563.

48. Kim MJ, Kim RJ, Ferracane J, Lee IB. Thermographic analysis of the effect of composite type, layering method, and curing light on the temperature rise of photo-cured composites in tooth cavities. *Dent Mater.* 2017;33(10):e373-e383.

49. Bouillaguet S, Caillot G, Forchelet J, Cattani-Lorente M, Wataha JC, Krejci I. Thermal risks from LED- and high-intensity QTH-curing units during polymerization of dental resins. *J Biomed Mater Res B Appl Biomater.* 2005;72(2):260-267.

50. Chang HS, Cho KJ, Park SJ, et al. Thermal analysis of bulk filled composite resin polymerization using various light curing modes according to the curing depth and approximation to the cavity wall. *J Appl Oral Sci.* 2013;21(4):293-299.

51. Panas A, Żmuda S, Terpiłowski J, Preiskorn M. Investigation of the thermal diffusivity of human tooth hard tissue. *International Journal of Thermophysics.* 2003;24(3):837-848.

52. Figueiredo de Magalhaes M, Neto Ferreira RA, Grossi PA, de Andrade RM. Measurement of thermophysical properties of human dentin: effect of open porosity. *J Dent.* 2008;36(8):588-594.

53. Choi SH, Roulet JF, Heintze SD, Park SH. Influence of cavity preparation, light-curing units, and composite filling on intrapulpal temperature increase in an in vitro tooth model. *Oper Dent.* 2014;39(5):E195-205.

54. Oberholzer TG, Makofane ME, du Preez IC, George R. Modern high powered led curing lights and their effect on pulp chamber temperature of bulk and incrementally cured composite resin. *Eur J Prosthodont Restor Dent.* 2012;20(2):50-55.

55. Hannig M, Bott B. In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources. *Dent Mater.* 1999;15(4):275-281.

56. Anusavice KJ, Shen C, Rawls HR. *Phillips' science of dental materials.* Elsevier Health Sciences; 2012.

57. Zarpellon DC, Runnacles P, Maucoski C, et al. Influence of Class V preparation on in vivo temperature rise in anesthetized human pulp during exposure to a Polywave((R)) LED light curing unit. *Dent Mater.* 2018;34(6):901-909.

58. Runnacles P, Arrais CA, Pochapski MT, et al. In vivo temperature rise in anesthetized human pulp during exposure to a polywave LED light curing unit. *Dent Mater.* 2015;31(5):505-513.

59. 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(6):485-490.

60. Balestrino A, Verissimo C, Tantbirojn D, Garcia-Godoy F, Soares CJ, Versluis A. Heat generated during light-curing of restorative composites: Effect of curing light, exotherm, and experiment substrate. *Am J Dent.* 2016;29(4):234-2240.

61. Guiraldo RD, Consani S, De Souza AS, Consani RL, Sinhoreti MA, Correr-Sobrinho L. Influence of light energy density on heat generation during photoactivation of dental composites with different dentin and composite thickness. *J Appl Oral Sci.* 2009;17(4):289-293.

62. Guiraldo RD, Consani S, Lympius T, Schneider LF, Sinhoreti MA, Correr-Sobrinho L. Influence of the light curing unit and thickness of residual dentin on generation of heat during composite photoactivation. *J Oral Sci.* 2008;50(2):137-142.

63. Vaidyanathan J, Vaidyanathan TK. Computer-controlled differential scanning calorimetry of dental composites. *IEEE Trans Biomed Eng.* 1991;38(4):319-325.