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Original Article

Mapping the horizontal thermal distribution profile of composite resins during polymerization using real-time infrared thermography

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Purpose: This study aimed to establish a technical protocol using real-time infrared thermography to visualize and analyze the horizontal thermal distribution profiles and spatial thermal gradients of composite resins during photopolymerization. The study evaluated and compared the polymerization heat of conventional and bulk-fill resins across various thicknesses from the perspective of spatial thermal gradients. **Materials and Methods:** Specimens of a flowable resin (G-aenial Flo) and a bulk-fill resin (SDR) were prepared in thicknesses from 0.5 to 5.0 mm. During light-curing with a high-intensity light-emitting diode curing light unit, thermal data were collected in real-time along a linear axis extending from the center of maximum temperature rise to the periphery. Due to the use of a single specimen per condition, the results were interpreted descriptively. **Results:** In all specimens, the peak temperature decreased as the distance from the center increased. SDR exhibited faster thermal response and superior spatial thermal homogeneity than G-aenial Flo across all thicknesses. Notably, SDR exhibited sustained thermal activity up to 5.0 mm, whereas the conventional flowable resin showed significantly reduced lateral thermal response at thicknesses beyond 2.5 mm. **Conclusion:** Real-time infrared thermography is an effective tool for analyzing the spatiotemporal dynamics and horizontal thermal profiles of composite resins. The spatial thermal analysis in this study provides critical technical insights for clinicians in selecting appropriate materials and layering techniques for deep cavity restorations. These thermographic findings represent an indirect assessment of polymerization behavior and do not directly indicate the degree of conversion. **(J Dent Rehabil Appl Sci 2026;42(2): 79-89)**

Key words: composite resins; dental materials; polymerization; thermography

Introduction

The clinical versatility of composite resins has led to the development of various formulations, including high-flow and bulk-fill types, designed to optimize physical properties and handling. These materials typically utilize dimethacrylate-based monomer systems, with their mechanical behavior governed by the characteristics and loading of inorganic fillers.[1] Flowable resins were initially introduced to improve cavity adaptation. Despite their initial limitations due to low filler content, subsequent modifications have enabled their application in posterior restorations.[1-3] However, care must be taken when applying these resins, as their polymerization shrinkage is greater than that of conventional packable composites.[4] Recently, high-flow bulk-fill composite resins have been commercialized to further simplify the restorative procedure. According to manufacturers, these high-flow bulk-fill resins are designed to exhibit reduced

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polymerization shrinkage compared to conventional flowable composites and allow for the polymerization of layers exceeding 4 mm in thickness in a single application.[4]

Photopolymerization occurs through an addition reaction of carbon-carbon double bonds (C=C), an exothermic process that inherently generates heat.[5] This reaction is triggered by visible light (400 - 500 nm) activating photoinitiators, such as camphorquinone, to generate free radicals.[6] High-intensity light-emitting diode (LED) curing units, often exceeding 1,000 mW/cm^2, have replaced older technology due to their superior spectral matching and efficiency.[7] However, such high irradiance can lead to substantial temperature increases during the curing process.[8]

Temperature rise during curing results from both radiant heat from the light source and the exothermic nature of the polymerization process.[9-11] Traditional contact-based methods such as thermal analysis and thermocouples have been used to measure temperature rise.[8,12-15] However, these methods require direct contact with the surface and can only measure the temperature at specific points.[16] In contrast, infrared thermography (IRT) offers a non-invasive alternative, utilizing high-resolution infrared cameras to visualize and quantify the spatial distribution of infrared radiation emitted during polymerization.[10,13,14] This technique has been widely used in research to measure temperature changes during polymerization. Infrared thermography detects emitted radiation and converts it into thermal images.[17] This method is extensively utilized in various industrial and medical fields for monitoring equipment and devices.[18]

Although IRT has been employed to monitor temperature changes, most dental studies have focused on temporal changes at a fixed thermal peak.[9,10,12] A previous study evaluated the relationship between increment thickness and peak temperature at the central axis.[19] However, the spatial homogeneity of polymerization heat across the restoration surface, which is critical for ensuring consistent curing in wide cavities, remains under-investigated. Therefore, this study aimed to map the horizontal thermal distribution profiles of conventional and bulk-fill flowable resins. The primary objective was to establish a spatiotemporal analysis protocol to visualize how spatial thermal gradients are influenced by material type and incremental thickness.

Materials and Methods

Fabrication of Resin Specimens

Two commercially available flowable composite resins, G-aenial Flo (GF; shade A2, GC Co., Tokyo, Japan) and a bulk-fill flowable resin, SDR (Universal shade, Dentsply Caulk, Milford, USA), were selected for this comparative spatial analysis (Table 1). Polymerization was performed using a high-intensity LED light-curing unit (Dr's Light, GoodDoctors Co., Seoul, Republic of Korea) equipped with an 8 mm diameter tip. To ensure irradiance stability, the light intensity was verified ten times at various intervals using a dedicated LED radiometer (Good Doctors Co., Incheon, Republic of Korea), and the mean value with standard deviation was calculated. Irradiance was recorded at 5, 10, 20, 40, and 80 s after activating the unit to assess short-term output stability. At each time point, the irradiance was measured 10 times, and the distribution of repeated measurements was summarized in Fig. 1. The irradiance output of the LED unit remained stable across the measured time points.

To evaluate the influence of increment thickness on the thermal profile, customized acrylic molds were prepared in 0.5 mm increments, ranging from 0.5 mm to 5.0 mm in total depth. Each mold contained a standardized central circular cavity with a diameter of 5.5 mm to accommodate the resin. Following a previously established protocol, a 0.5 mm-thick acrylic plate was bonded to the bottom of each mold to create a standardized confined cavity environment (Fig. 2).[19] This design ensured consistent resin containment and a reproducible geometry for spatiotemporal analysis. The respective resins were injected into the molds, covered with a 38-μm celluloid strip (SKY Striproll 10, Suki-Dental, Seoul, Republic of Korea), and compressed with a glass plate to eliminate air voids and ensure a planar, uniform upper surface. For high-fidelity infrared thermo-

Table 1. Materials and composition

Product (Abbreviation)	Manufacturer Batch no.	Matrix system	Filler system Filler load (wt % / vol%)	Shade
G-aenial Flo (GF)	GC Co., Tokyo, Japan, 1310081	UDMA, Bis-MEPP, TEGDMA	SiO_2, Sr glass (69 / 50)	A2
SDR (SDR)	Dentsply Caulk, Milford, USA 0608	Modified UDMA, EBPDMA, TEGDMA	Ba-Al-F-B-silicate glass (68 / 44)	U

UDMA, urethane dimethacrylate; EBPDMA, Ethoxylated Bisphenol-A Dimethacrylate; Bis-MEPP, 2,2-Bis (4-methacryloxypolyethoxyphenyl) propane; TEGDMA, triethylene glycol dimethacrylate.

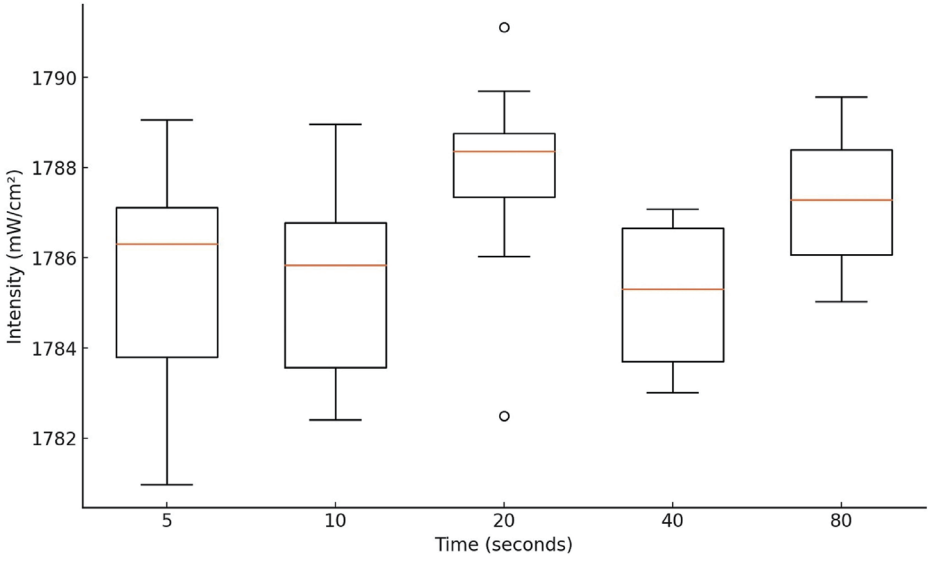

Fig. 1. Measured irradiance (mW/cm²) of the LED light-emitting diode curing unit at predefined time points after activation (5, 10, 20, 40, and 80 s) using a radiometer (n = 10 measurements per time point). The boxplots show the distribution of repeated measurements at each time point, indicating irradiance stability over time. Empty circles indicate outliers.

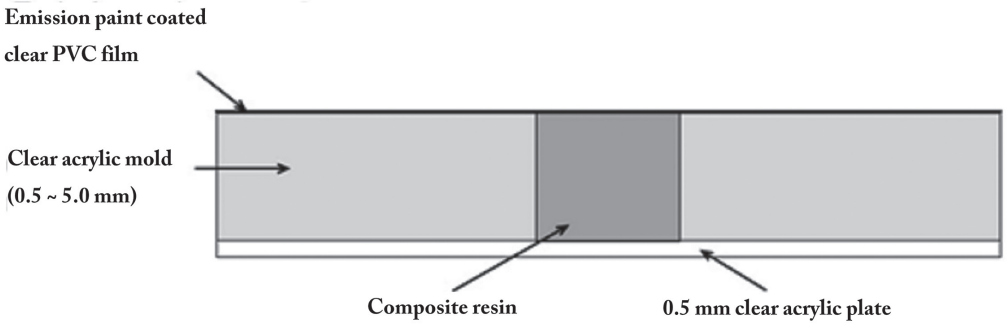

Fig. 2. Schematic representation of the acrylic cavity mold used for resin specimen preparation. The emissive paint-coated surface is used for thermal imaging calibration.

graphic mapping, the specimen surface was coated with a matte black emissive paint (Krylon 4290 Ultra Flat Black, Krylon Industrial, Cleveland, USA) to standardize the emissivity to 0.97. This step was critical to minimize thermal reflections and ensure that the captured radiation accurately represented the spatial temperature distribution. The painted surface was allowed to dry thoroughly before proceeding with testing.

Real-time Thermographic Data Acquisition

To monitor the thermal behavior during polymerization, a high-resolution infrared thermographic camera (FLIR SC620, FLIR Systems AB, Stockholm, Sweden) was utilized. All thermographic recordings were performed within a light-controlled darkroom at a stabilized ambient temperature to eliminate potential artifacts from external radiation or stray light sources. The LED curing unit was secured to a rigid stand, with its light-emitting tip positioned 10 mm beneath the specimen's base to ensure uniform and reproducible light delivery across all samples. The IRT camera was mounted 100 mm superior to the specimen, with the lens precisely aligned perpendicular to the upper surface to facilitate accurate horizontal thermal mapping. Thermal data acquisition was conducted at a frame rate of 30 Hz, allowing for high-speed capture of the transient exothermic reaction. The captured frame-by-frame radiance data were subsequently processed using software (FLIR Tools, FLIR Systems AB), which converted the raw infrared signals into discrete temperature values at 1-second intervals for spatiotemporal analysis.

Spatiotemporal Thermal Mapping and Descriptive Analysis

For each resin specimen, the thermal centroid, defined as the point of maximum temperature rise, was identified using the analysis software. To map the horizontal thermal distribution, temperature values were recorded within a 5.0 mm diameter region centered on this centroid across all tested thicknesses. The primary analysis involved extracting temperature data along a 5.0 mm linear axis (extending 2.5 mm radially from the centroid) to visualize the spatial thermal gradient (Fig. 3). These profiles were recorded at 1-second intervals from the initiation of light-curing until the peak exothermic temperature was reached.

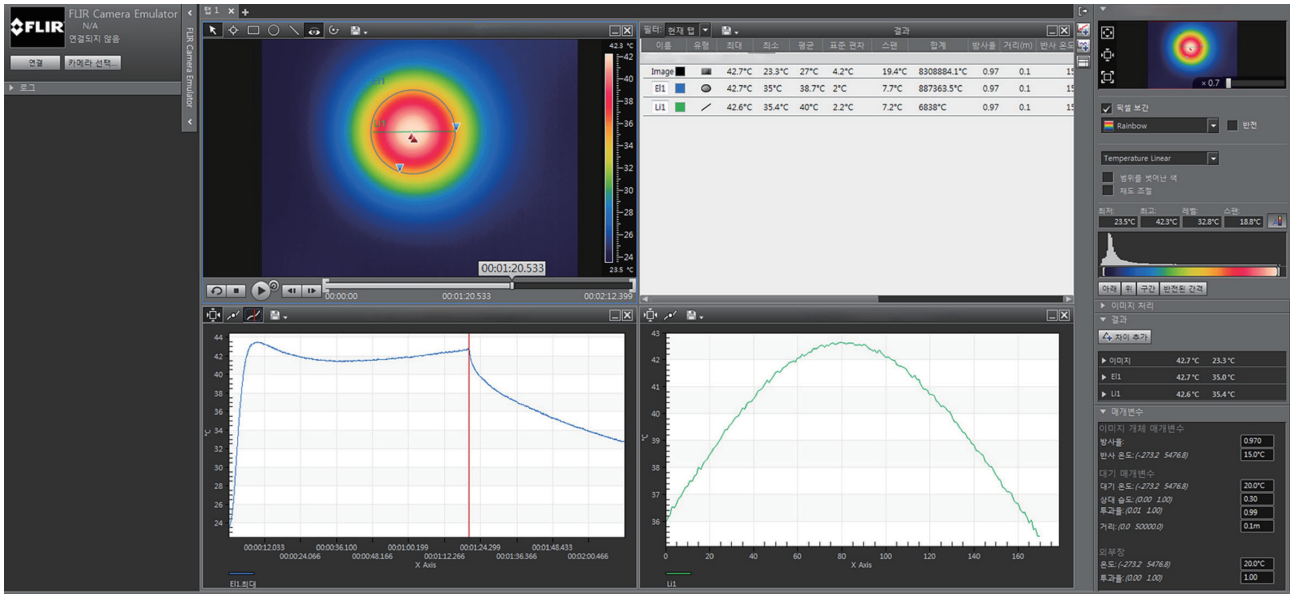

Fig. 3. Thermal image captured using infrared camera software during curing of SDR (bulk-fill flowable resin) at 2.0 mm thickness. Color scale represents temperature (°C).

Based on these spatiotemporal temperature datasets, temperature rise graphs were plotted for each resin across all thicknesses to analyze the spatial temperature differential between the center and the periphery. Data interpretation focused on descriptive trends in spatial thermal behavior, specifically comparing the horizontal profiles between the GF and SDR. No statistical analyses were performed, as the goal of this study was to explore spatial thermal behavior rather than test specific hypotheses. Given that only one sample per condition was measured due to the exploratory nature of the study, statistical analyses were not feasible and were therefore omitted. Instead, the results were interpreted descriptively, focusing on identifying material-specific and thickness-dependent trends in spatial thermal dynamics.

Results

The spatiotemporal thermal distribution profiles for both SDR and GF revealed a definitive spatial temperature differential between the thermal centroid and the peripheral regions. Across all experimental conditions, the peak temperature consistently exhibited a radial decline as the distance from the centroid increased toward the 2.5 mm periphery (Fig. 4, 5).

At a 2.0 mm thickness, a significant spatial gradient

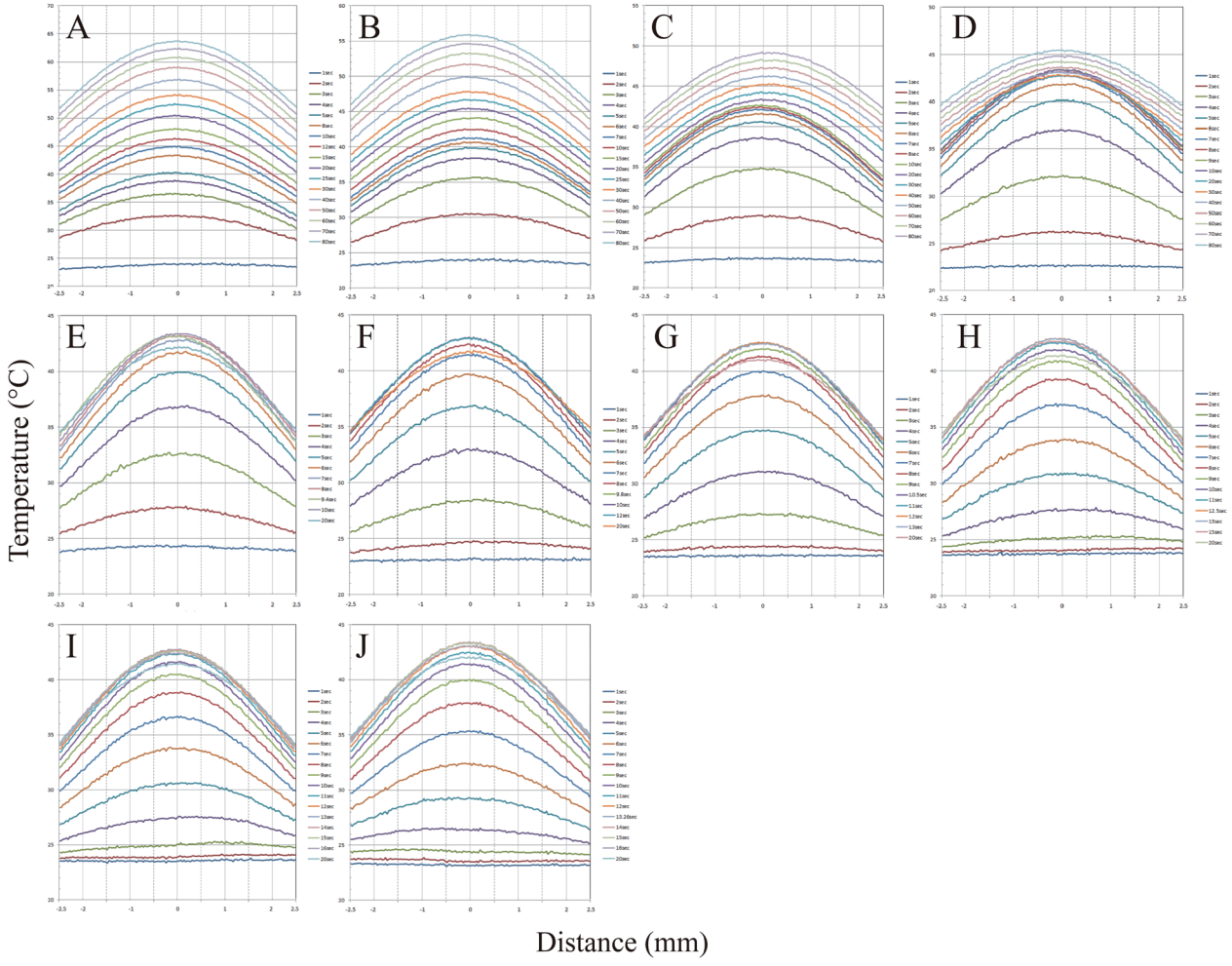

Fig. 4. Temperature rise (°C) across various resin thicknesses (mm) of SDR (bulk-fill flowable composite resin) around the point of highest temperature rise according to the curing time: (A) 0.5 mm; (B) 1.0 mm; (C) 1.5 mm; (D) 2.0 mm; (E) 2.5 mm; (F) 3.0 mm; (G) 3.5 mm; (H) 4.0 mm; (I) 4.5 mm; (J) 5.0 mm. Note: Temperature curves represent a single measurement per condition.

was identified during the initial stages of polymerization (Fig. 4D, 5D). Specifically, the temperature at the 2.5 mm periphery was approximately 10% to 15% lower than at the centroid during the peak exothermic phase. However, this spatial differential gradually narrowed as the curing time reached 80 seconds, eventually stabilizing at a smaller relative difference.

SDR exhibited greater spatial thermal homogeneity than GF across all tested thickness levels. In SDR specimens, the horizontal thermal profile remained relatively consistent from the center to the edge (Fig. 4A - 4J). Conversely, GF exhibited a steeper thermal decay toward the periphery, a trend that became more pronounced as the increment thickness increased (Fig. 5E - 5J).

At incremental thicknesses of 1.5 mm or less, both resins showed a continuous and rapid temperature increase over time without a distinct early peak (Fig. 4A - 4C, 5A - 5C). For thicknesses exceeding 2.5 mm, a clear divergence in spatial behavior was noted between the two materials. SDR maintained over 80% of its peak thermal activity up to a thickness of 5.0 mm (Fig. 4E - 4J). In contrast, the lateral thermal response of GF was markedly reduced at these depths, suggesting reduced thermal response in the peripheral areas of thicker increments (Fig. 5E - 5J).

The time required to reach the peak exothermic temperature increased proportionally with specimen thickness for both resins, particularly beyond 2.0 mm. SDR reached its maximum thermal output ear-

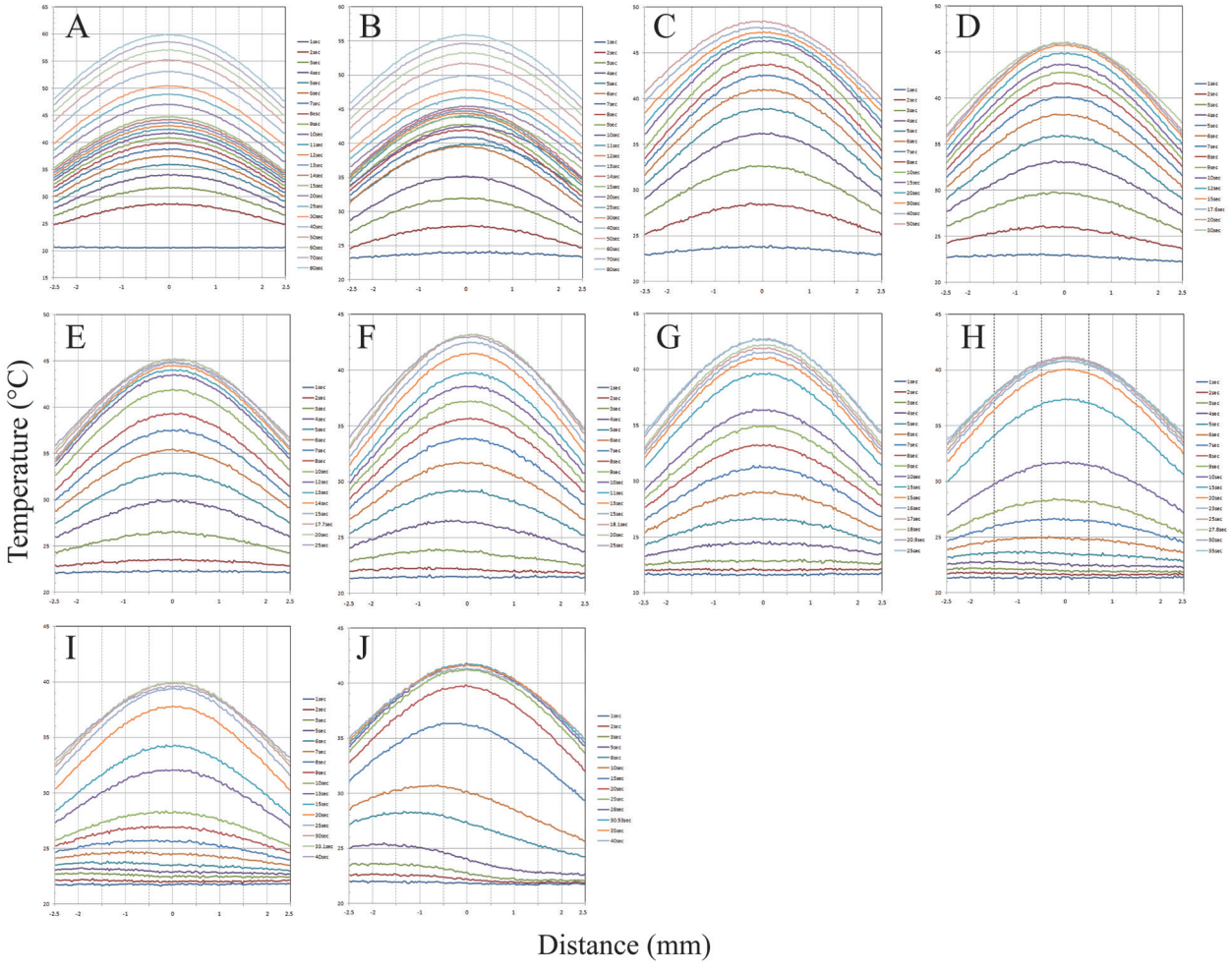

Fig. 5. Temperature rise for different resin thickness of G-aenial Flo (flowable composite resin) around the point of highest temperature rise according to the curing time: (A) 0.5 mm; (B) 1.0 mm; (C) 1.5 mm; (D) 2.0 mm; (E) 2.5 mm; (F) 3.0 mm; (G) 3.5 mm; (H) 4.0 mm; (I) 4.5 mm; (J) 5.0 mm. Note: Temperature curves represent a single measurement per condition.

lier than GF across all tested thicknesses, suggesting a difference in thermal response patterns between the two materials (Fig. 4, 5). While these results are based on a single measurement per condition, they indicate that bulk-fill resins reached thermal maxima earlier than conventional flowable resins under the tested conditions.

Discussion

This study showed that real-time IRT mapping is an effective tool for analyzing the spatiotemporal thermal behavior associated with photopolymerization of composite resins. Unlike traditional thermal analysis or thermocouples, which are restricted to single-point measurements, the IRT-based protocol established here allows for a comprehensive visualization of the horizontal thermal distribution. Conventional point-measurement methods may yield inconsistent results depending on the specific location of the probe. Consistent with the findings of Chang et al., our results confirm that temperature profiles are not uniform across the light-exposed surface.[20] In contrast, IRT mapping provides an advantage by identifying the thermal centroid and capturing the overall spatial temperature gradient, and it allows for precise temperature comparisons over very short time intervals, thereby enhancing the utility of this technique.

Thermal-based evaluation of polymerization has been reported to show correlations between exothermic profiles and the degree of conversion (DC) in previous studies using differential thermal analysis (DTA) and Fourier transform infrared spectroscopy (FTIR).[15,21] This correlation is particularly relevant for resins containing diluent monomers like Triethylene Glycol Dimethacrylate (TEGDMA), such as GF and SDR. The two resins used in this study are flowable types, with Urethane Dimethacrylate (UDMA), a less viscous base monomer than bisphenol A-glycidyl methacrylate (Bis-GMA), as the primary matrix, and both resins also contain TEGDMA. Although the exact UDMA-to-TEGDMA content ratio of the two materials is unknown, the thickness-dependent thermal response observed in this study may provide only indirect information on polymerization behavior within the same material and should not be interpreted as a direct indicator of the degree of conversion. The proportion of TEGDMA in the resin matrix can influence thermal behavior during photopolymerization, particularly in deeper layers. Since SDR and GF both contain TEGDMA, future studies should further analyze the compositional differences to determine their precise impact on thermal behavior and curing outcomes.

In our spatial mapping, GF exhibited effective thermal activity only up to 2.5 mm, with a significant decline in peripheral temperature at greater thicknesses. Conversely, SDR maintained consistent spatial thermal behavior even at 5.0 mm, aligning with previous microhardness studies that reported its superior depth of cure.[3,4] This suggests that SDR possesses a greater curing capacity, likely due to its modified UDMA matrix and enhanced translucency. The results of this study demonstrate that bulk-fill flowable composite resin achieves deeper and faster polymerization compared to conventional flowable resins, particularly in thicker layers. The greater curing capacity observed in SDR may be attributed to several material-related factors. Bulk-fill flowable composite resins are specifically engineered to enhance light transmission and polymerization efficiency in deeper layers.[3,4] SDR contains a modified UDMA-based resin matrix, which has been reported to exhibit lower viscosity and improved radical mobility compared to conventional flowable resins.[4] In addition, the increased translucency of bulk-fill materials facilitates deeper light penetration, allowing more uniform energy delivery throughout thicker increments.[11] These compositional and optical characteristics may contribute to the more homogeneous spatial thermal profiles observed in SDR, particularly at greater thicknesses.

However, it should be emphasized that the present findings are based on thermal behavior and do not directly represent the degree of conversion. Therefore, the proposed mechanisms should be interpreted as plausible explanations rather than definitive evidence of superior polymerization performance. The observed thermal profiles suggest that SDR ex-

hibited a more sustained and homogeneous thermal response than GF under the tested conditions. While further investigation is necessary, the findings suggest that temperature measurement methods may be used to characterize spatiotemporal thermal behavior during light-curing and could complement direct assessments of curing outcomes in future studies.

This study also has its limitations. The thermal profiles in thinner layers (0.5 to 1.5 mm) were dominated by radiant heat from the LED unit, complicating the isolation of the exothermic reaction (Fig. 4A - 4C, 5A - 5C). Importantly, the thermal profiles captured by infrared thermography represent the combined heat contribution from the light-curing unit and the resin system, rather than isolating the exothermic heat generated solely by the polymerization reaction. In addition, the use of a black emissive coating on the specimen surface, although necessary to standardize emissivity and improve the accuracy of infrared thermographic measurements, represents a limitation from a clinical perspective. This surface treatment may alter the original optical properties of the composite resin, including light transmission and surface reflectance. In particular, the enhanced translucency of bulk-fill flowable resins, which contributes to their curing behavior under clinical conditions, may have been partially masked by the emissive coating.

Therefore, the thermal profiles observed in this study should be interpreted as measurements obtained under standardized experimental conditions rather than as direct representations of in vivo polymerization behavior. Therefore, the present thermal mapping should be interpreted as an indirect assessment of polymerization behavior rather than a direct measure of curing depth or degree of conversion. Future studies incorporating direct assessments such as FTIR/Raman spectroscopy or microhardness testing would be required to validate the relationship between spatial thermal patterns and curing outcomes. In addition, future studies should incorporate strategies to minimize external thermal influences and investigate temperature rise across different resin thicknesses to establish appropriate application criteria for infrared thermography in polymerization research.

From a clinical perspective, the spatial homogeneity observed in SDR supports its use in wide and deep cavities, ensuring reliable polymerization even in peripheral regions. This capacity to maintain a stable horizontal thermal profile across greater thicknesses offers advantages for simplifying restorative workflows while minimizing the risk of internal voids or incomplete curing. Moreover, the application of infrared thermographic cameras in evaluating the polymerization characteristics of composite resins appears to hold significant potential and value for future studies.

Conclusion

Within the limitations of this exploratory study, several key conclusions can be drawn regarding the spatiotemporal polymerization dynamics of composite resins. This study showed that real-time IRT is an effective, non-contact tool for monitoring thermal behavior during light-curing, providing a more comprehensive visualization of horizontal thermal distribution compared to traditional point-measurement methods. Our findings indicate that temperature rise during light-curing is not uniform across the specimen surface, but rather exhibits a radial decline from the thermal centroid toward the periphery. In the comparative analysis of materials, SDR-showed more homogeneous and sustained spatial thermal behavior across increased increment thicknesses up to 5.0 mm under the tested conditions, whereas the conventional flowable resin, GF, exhibited a marked reduction in peripheral thermal response at thicknesses exceeding 2.5 mm. These observations suggest that bulk-fill flowable resins may offer practical advantages in achieving more uniform thermal behavior in deep and wide restorations. Ultimately, the spatial thermal mapping protocol established in this study provides valuable technical insights for clinicians in selecting appropriate materials and application techniques to minimize the risk of incomplete curing in clinical practice.

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실시간 적외선 열화상 촬영을 이용한 복합 레진 중합열의 수평적 열 분포 프로파일 분석

배꽃별[1] 조교수, **조영태**[2] 교수, **이빈나**[1] 교수, **장훈상**[1] 교수, **황윤찬**[1] 교수, **황인남**[1]* 교수

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목적: 본 연구는 실시간 적외선 열화상 기술을 활용하여 복합 레진 광중합 시 발생하는 열의 공간적 분포 및 수평적 확산 패턴을 시각화하고 분석하는 프로토콜을 제시하고자 하였다. 기존 유동성 레진과 벌크필 레진의 두께별 중합열 분포를 공간적 열 구배 관점에서 비교 평가하였다.

연구 재료 및 방법: 본 연구에서는 G-aenial Flo (유동성 레진)와 SDR (벌크필 레진)을 0.5 mm에서 5.0 mm 두께 시편으로 제작하고 고강도 발광 다이오드 광중합기를 사용하여 중합을 진행했다. 적외선 열화상 카메라를 이용하여 최대 온도 상승 중심에서 주변부로 이어지는 선형 축을 따라 수평적 열 분포 데이터를 실시간으로 수집했다. 각 조건당 하나의 시편만 사용했기 때문에 결과는 기술적으로 해석했다.

결과: 모든 시편에서 열 중심부로부터의 거리가 멀어질수록 최고 온도가 감소하였다. SDR은 모든 두께에서 G-aenial Flo보다 빠르고 균일한 공간적 열 발생을 보였다. 특히 SDR은 5.0 mm에서도 효과적인 중합 활성을 유지했으나, 일반 유동성 레진은 2.5 mm 이상에서 주변부 열 반응이 현저히 저하되었다.

결론: 실시간 적외선 열화상 촬영은 복합 레진의 중합을 비접촉으로 모니터링할 수 있는 유용한 도구이다. 본 연구의 공간적 열 분석은 임상의에게 깊은 와동의 수복 시 적절한 재료 선택과 적층 기법 결정에 중요한 기술적 통찰을 제공한다.

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주요어: 복합 레진; 치과 재료; 중합; 열화상 기술

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