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ORIGINAL ARTICLE

Effectiveness of photopolymerization in composite resins using a novel 445-nm diode laser in comparison to LED and halogen bulb technology

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Abstract
Challenges especially in the minimal invasive restorative treatment of teeth require further developments of composite polymerization techniques. These include, among others, the securing of a complete polymerization with moderate thermal stress for the pulp. The aim of this study is to compare current light curing sources with a blue diode laser regarding curing depth and heat generation during the polymerization process. A diode laser (445 nm), a LED, and a halogen lamp were used for polymerizing composite resins. The curing depth was determined according to the norm ISO 4049. Laser output powers of 0.1, 0.5, 1, and 2 W were chosen. The laser beam diameter was adapted to the glass rod of the LED and the halogen lamp (8 mm). The irradiation time was fixed at 40 s. To ascertain ΔT values, the surface and ground area temperatures of the cavities were simultaneously determined during the curing via a thermography camera and a thermocouple. The curing depths for the LED (3.3 mm), halogen lamp (3.1 mm) and laser$_{(0.5/1\ \mathrm{W})}$ (3/3.3 mm) showed no significant differences ($p < 0.05$). The values of $\Delta T_{\mathrm{surface}}$ as well as $\Delta T_{\mathrm{ground}}$ also showed no significant differences among LED, halogen lamp, and laser$_{(1\ \mathrm{W})}$. The $\Delta T_{\mathrm{surface}}$ values were 4.1_{LED}, $4.3_{\mathrm{halogen\ lamp}}$, and 4.5 °C for the laser while the $\Delta T_{\mathrm{ground}}$ values were 2.7_{LED}, $2.6_{\mathrm{halogen\ lamp}}$, and 2.9 °C for the laser. The results indicate that the blue diode laser (445 nm) is a feasible alternative for photopolymerization of complex composite resin restorations in dentistry by the use of selected laser parameters.

Keywords Restorative dentistry · Photopolymerization · Composite resin · Blue diode laser · Curing depth · Polymerization temperature

Introduction

In dentistry, diode lasers emitting light in the wavelength range of 0.8–1 μm have been applied recently for surgery and microbial decontamination in endodontics and periodontics, respectively [1, 2]. The new blue diode laser (445 nm), which is currently being used in surgery [3], might be particularly interesting for restorative dentistry. This wavelength is close to the absorption maximum of the photoinitiator camphorquinone (~ 465 nm) [4], the most widely used photoinitiator for the photopolymerization of dental composite resins [5].

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Halogen light curing units, introduced in the end of 1970s [6], and the LED curing units, launched in the beginning of the millennium, are mainly used in clinical routine today [7, 8]. In halogen light curing units, just a very small fraction of the emitted radiation is located in the interesting wavelength range of blue light [9] whereas the main part, found in the infrared spectral region, is radiated as heat. Therefore, a ventilator must be used for cooling the units. Moreover, to ensure constant power, the halogen bulb needs to be replaced every 6 months at the latest [10].

The emitted radiation of the LED curing units is in the wavelength range of 438–501 nm and showing a sharp maximum at 465 nm [11]. Since infrared (thermal) radiation is not emitted, these units do not need an additional internal cooling device. A defined wavelength range can be adjusted to the respective material. Besides being easy to handle and maintain through their battery operation and compact design, LED units also show a long lifespan [12].

Even though its wavelength of 488 nm is beyond the maximum range of the photoinitiator camphorquinone, the argon ion (Ar^+) laser has been used effectively for photopolymerization of composite materials as shown in earlier studies [13–20]. However, the Ar^+-laser could not be established in dental practice because of its complex technology, spacial limitations in clinical routine [1] and its high costs.

All the benefits of the aforementioned curing light sources can be harnessed in the new diode laser technology, exploiting the emission of light with the wavelength 445 nm. In adhesive dentistry, the light sources for the curing process have to be continuously enhanced to keep stride with new requirements. High intensities are needed to ensure proper photopolymerization for the adhesion of ceramic objects [21]. Moreover, these curing light units have to ensure a low temperature development in deep cavities to protect the pulp tissue from thermal stress [22]. A thin and flexible light guide is also required to guarantee full illumination of cavities that are difficult to access, e.g., root canals [18] and of minimally prepared cavities [23]. The LED and the halogen light sources have reached their technological limits to meet these requirements. By contrast, a diode laser in the blue spectral range generates high intensities, has a sharply defined wavelength range, and can be easily equipped with an optical fiber, thereby complying with the new requirements of the modern adhesive dentistry.

Consequently, the aim of this current study is to investigate, whether a blue diode laser may be a viable alternative to a LED or a halogen lamp as light source in the photopolymerization of composite resins in modern adhesive dentistry. The curing depth and temperature response were selected as basic indicators to determine equivalent polymerization properties.

Materials and methods

Light curing units

The halogen curing unit (Optilux 501, Kerr GmbH, Rastatt, Germany) emits light of wavelengths ranging from 400 to 510 nm and generates an intensity of 830 mW/cm^2. The intensity was measured with the radiometer integrated in the control device. Light is guided from the source using a glass rod having a diameter of 8 mm.

The LED unit (Optima 10, B.A. International Ltd., Northampton, UK) emits wavelengths ranging from 420 to 505 nm and it generates an intensity of 1170 mW/cm^2. This system has a light guiding glass rod designed exactly like that of the halogen unit (∅ = 8 mm).

Emitting light of a wavelength of 445 nm, the diode laser (SIROLaser Blue, Sirona, Bensheim, Germany) was used with different power settings (0.1, 0.5, 1, and 2 W) in the continuous wave mode. The light guiding system (NA = 0.22) is a flexible quartz glass fiber with a diameter of 320 μm. The beam diameter (beyond the fiber) of the laser device was adapted to the light sources mentioned above (∅ = 8 mm). The resulting intensities are shown in Table 1.

All power settings of the curing units were controlled and measured with an energy/power meter (LabMax Top) combined with a PM10 detector (Coherent, Santa Clara, USA). Intensities were calculated by considering the corresponding light guiding devices of the curing units.

Figure 1 shows the emission spectra of the applied curing units used in comparison to the absorption spectrum of camphorquinone.

Composite material

The microhybrid composite resin XRV Herculite A3 Enamel (Kerr GmbH, Rastatt, Germany) was used for all the measurements. Widely employed in dental practice [24], this material has been well examined in the materials sciences [25]. It was always applied with the Undiose dispenser gun™ (delivery system, Kerr GmbH, Rastatt, Germany).

Curing depth measurements

The curing depth was determined according to the ISO Norm 4049 [26]. The corresponding sample holder for curing depth measurements consists of stainless steel with a cavity diameter of 4 mm and a cavity depth of 12 mm, in accordance with the ISO norm. For sample removal, the sample holder could be separated in two parts. After the cavity was filled with composite, the opening was covered with a coverslip (thickness, 0.13–0.16 mm) to avoid an oxygen inhibition layer. The irradiation time of the composite was 40 s for all light sources. After removal of the irradiated sample, the non-cured part of the composite resin was scraped away with a plastic spatula. The length of the cured composite resin part was measured and, in according to the ISO Norm, was divided by a factor of 2 to determine the real curing depth.

For each curing unit and power setting, 10 irradiations were carried out under room temperature (23.5 ± 0.5 °C). The schematic experimental setup is shown in Fig. 2a.

Temperature measurement devices

A thermography camera (VarioCam® hr head, InfraTec GmbH, Dresden, Germany) and the recording analysis software IRBIS® 3 professional (Infratec GmbH) were used to measure the surface temperature.

The ground area temperature was captured by a thermocouple connected to a digital temperature display device (TDA-3000, Jumo GmbH, Fulda, Germany) in a 6-mm cavity depth.

Table 1 Resulting intensities (mW/cm^2) on the sample surface for irradiation by the different light curing sources in dependency of the beam diameter and the power

Source	Halogen	LED	Diode laser			
Power [W]	–	–	0.1	0.5	1	2
Intensity (∅ = 8 mm)	830	1170	198.9	994.7	1989	3979
Intensity (∅ = 1.8 mm)	–	–	–	–	39,298	–

Surface temperature measurements

The surface temperature was determined on a rectangular cavity of 9 mm × 4 mm × 3 mm in a plastic sample holder.

The temperature was recovered over the total irradiation time (T_{IR} = 40 s). The temperature difference (ΔT) was calculated between T_{MAX} (maximum temperature) and T_{START} (T_{IR} = 0 s) at room temperature (23.5 ± 0.5 °C).

Thirteen irradiations were performed using the laser (1 W) and the halogen curing unit, respectively. For the LED curing unit experiments, 10 irradiations were carried out at room temperature. Figure 2b presents the schematic setup of the experiments.

Ground area temperature measurements

The ground area temperature was also determined using a stainless steel sample holder having a cylindrical cavity with a diameter of 4 mm and a depth of 6 mm. After the cavity was filled with composite, the upper opening was covered with a coverslip. The temperature was recorded as stated for the surface temperature measurements.

Whereas 12 experiments each were performed with the laser (1 W) and the LED curing unit. Eleven experiments were carried out with the halogen curing unit under room temperature (23.5 ± 0.5 °C), respectively.

An additional 11 experiments were performed with the laser (1 W), whereby the beam diameter was reduced down to 1.8 mm. The corresponding intensity is given in Table 1.

The schematic setup of the experiment is shown in Fig. 2c.

Statistical evaluation

The curing depths as well as temperature measurements were tested regarding normal distribution. If a normal distribution was present (Shapiro-Wilks test, $p > 0.05$), the variance homogeneity (Levene test, $p > 0.05$) and, subsequently, the single factor variance analysis (ANOVA) were conducted. If significant differences appeared, the Bonferroni test was carried out.

If the distribution was not normal ($p < 0.05$) the Kruskal-Wallis test was used to verify significant differences in common. If a significant difference occurred, the Mann-Whitney *U* test was applied.

Results

Curing depth

For the curing depth measurements, no normal distribution was present. The laser (1 W) achieved a curing depth of 3.3 ± 0.1 mm. An increase of up to 3.7 ± 0.1 mm (12%) resulted by doubling the laser power (2 W) and a reduction of 9% down to 3.0 ± 0.1 mm was measured by halving the laser power (0.5 W). The laser (0.1 W) achieved a curing depth of 2.3 ± 0.1 mm.

The achieved curing depth with the LED curing unit was 3.3 ± 0.1 mm and with the halogen curing unit 3.1 ± 0.1 mm.

No significant differences were measured among the laser (0.5 W and 1 W), the LED and the halogen curing units. The comparison of the halogen curing unit and the laser (0.1 W and

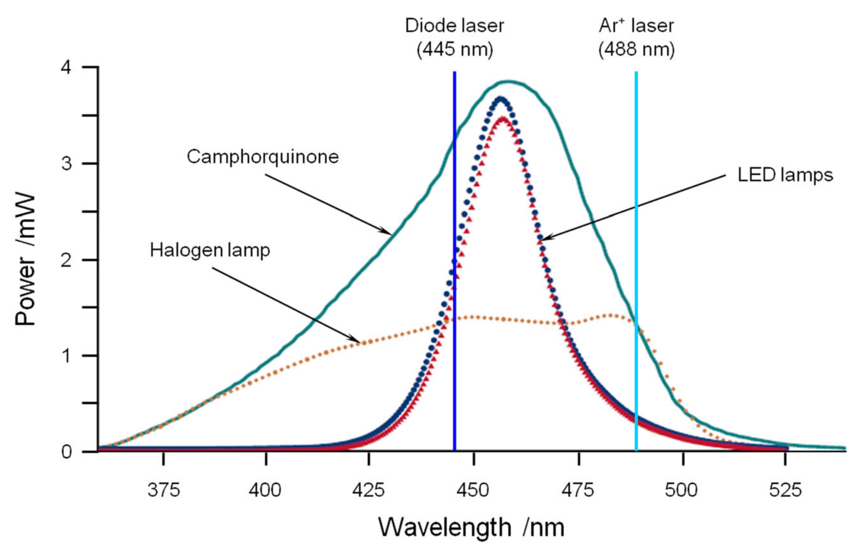

Fig. 1 Absorption spectrum of camphorquinone in relation to the different emission spectra of various light curing sources in the blue spectral range: Halogen lamp, LED, Ar^+ laser and diode laser

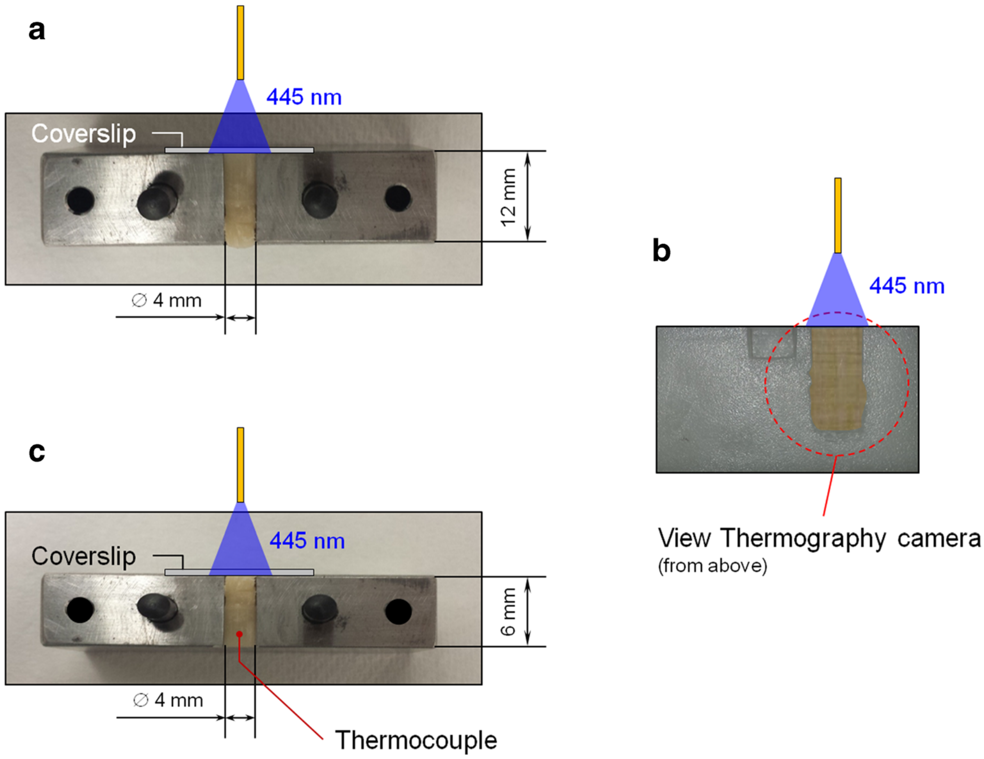

Fig. 2 **a**, **b**, **c** The experimental setups for the different measurements in principle. A side view is given for **a** and **c**, whereby irradiation was carried out from the top. A sample holder made of stainless steel was used as an artificial cavity according to the ISO Norm 4049. The cavity is filled with composite resin. For a better removal after curing, the sample holder was separated in two parts. To determine the curing depth, the thickness of the sample holder was 12 mm (**a**), for ground area temperature measurements the thickness of the sample holder was 6 mm (**c**). A rectangular plastic sample holder for surface temperature measurements was used in **b** and is presented in the thermography camera view from above. The red circle represents the measuring area of the thermography camera. The cavity is filled with composite resin. Irradiation was carried out parallel to the surface level

0.5 W) also showed no significant differences. No significant differences were found between the laser (1 W and 2 W) and LED curing unit as well. The results of the curing depths are summarized in Fig. 3. The corresponding *p*-values are shown in Table 2.

Surface temperature measurements

The surface temperature measurement shows also no normal distribution for the statistical evaluation. All light sources produced a temperature increase in a range of between 4.1 and 4.5 °C, whereby no significant differences could be observed among the three units (p values ≥ 0.073). The laser (1 W) induced an increase of $\Delta T = 4.5 \pm 0.5$ °C, the halogen curing unit an increase of 4.3 ± 0.2 °C and the LED curing unit an increase of 4.1 ± 0.2 °C. Figure 4 depicts the measured temperature increases.

Ground area temperature measurements

A normal distribution occurred for this measurement. The laser (1 W) and the other light sources produced a temperature increase ranging from 2.6 to 2.9 °C, whereby no significant differences could be found among the three units ($p = 0.181$). The laser (1 W) induced a temperature increase of 2.9 ± 0.4 °C, the LED curing unit an increase of 2.7 ± 0.2 °C and the halogen curing unit an increase of 2.6 ± 0.2 °C.

Regarding the ground area temperatures, a significance was found among the different beam diameters (p values > 0.001). The laser (1 W, ∅ = 1.8 mm) generated a ΔT of 5.4 ± 0.6 °C compared to the values of the laser (1 W, ∅ = 8 mm), the LED curing unit and the halogen curing unit mentioned above. Figure 5 shows the ΔT values of the ground area temperatures.

Discussion

The objective of this feasibility study is to investigate, whether the blue diode laser (445 nm) is suitable for the photopolymerization of composite resins in restorative

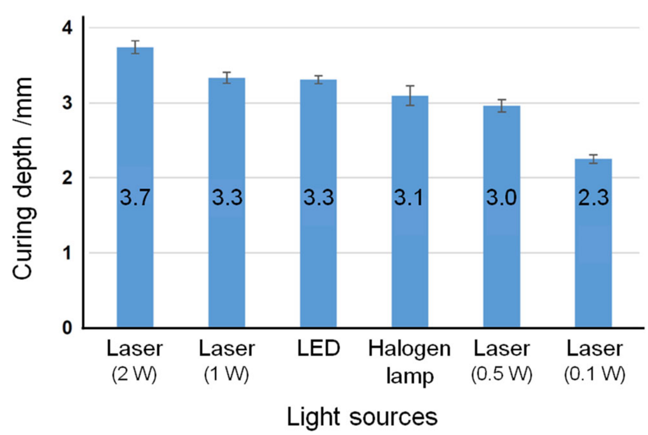

Fig. 3 Curing depth depending on the different light curing sources, as well the dependence of the laser output power is presented in the figure. In relation to the halogen lamp and the LED, the laser at 0.5 and 1 W shows comparable results in the curing depth

Table 2 Statistical evaluation (p values) given for the curing depth measurement. Italicized entries show no significant difference ($p > 0.05$)

	Laser (0.1 W)	Laser (0.5 W)	Halogen lamp	LED	Laser (1 W)	Laser (2 W)
Laser (0.1 W)	–	*1*	*0.227*	> 0.001	> 0.001	> 0.001
Laser (0.5 W)	*1*	–	*1*	*0.079*	*0.054*	> 0.001
Halogen lamp	*0.227*	*1*	–	*0.775*	*0.579*	0.001
LED	> 0.001	*0.079*	*0.775*	–	*1*	*0.579*
Laser (1 W)	> 0.001	*0.054*	*0.579*	*1*	–	*0.775*
Laser (2 W)	> 0.001	> 0.001	0.001	*0.579*	*0.775*	–

dentistry. The curing depth, the surface temperature, and the ground area temperature were measured and compared with those of halogen and LED curing units according to approved clinical protocols. The experiments were carried out under standardized in vitro conditions. Furthermore, a widely used microhybrid composite resin was applied with regard to clinical relevance [24].

The curing depth was measured with different laser output power settings in accordance with the norm ISO 4049 [26]. Even though the determination of the curing depth is a commonly employed method [27, 28], it is also considered to be overestimated [29, 30]. Further studies with special methods like the hardness test of Vickers [31], the degree of conversion [32, 33], and the penetration resistance with a penetrometer [11, 34] should be undertaken. Afterwards, a statement can be made whether the different laser output settings affect the physical properties of the polymerized composite. A conclusion might be drawn if the safety factor stipulated by the ISO Norm is adequate or needs to be modified [30].

The measurements of the surface temperature were carried out with one cavity size. The upper cavity side oriented to the thermography camera was not shielded against the radiation emitted by the light curing unit. This additional radiation occurs, e.g., by the restauration of class II cavities and caused a stronger polymerization reaction [35]. Therefore, the experimental setup can be considered as a worst-case situation. Modified cavity designs and sizes should be taken under consideration in future investigations.

The measurements of the ground area temperature were performed in a 6-mm deep cavity, which was completely filled with composite. The focus was to compare the induced temperature by the three light curing units during the polymerization process. In clinical practice, a 6-mm deep cavity should be restored with the layer technique and not be filled at once [36].

The laser with an output power of 1 W and a beam diameter of 8 mm was comparable to halogen and LED polymerization devices in both temperature measurements. Thus, the material properties of the polymerized composite like, e.g., the degree of conversion [32] and the shrinkage [37] should be investigated by applying these laser parameters in further studies.

A plastic sample carrier was employed in the surface temperature measurements and a stainless steel sample carrier was used in the ground area measurements. The thermal conductivity of plastic (0.23 W/mK) and stainless steel (13–17 W/mK) [38] differs from that of enamel (0.75–0.83 W/mK) and dentin (0.45–0.67 W/mK) [39]. Therefore, prospective investigations should be conducted to obtain information about the temperature development in sample carriers that have a similar thermal conductivity like the teeth structures.

All experiments were performed under in vitro conditions in a laboratory setting at room temperature. To gain knowledge about what happens under realistic conditions inside the oral cavity, further studies should be undertaken.

The results of the curing depth experiments show that the diode laser in the high power output settings (1 W, 2 W) achieved curing depths like those of the halogen and the LED lamps. In addition, the curing depths of the laser in a low power output setting (0.1 W, 0.5 W) were comparable to those of the two aforementioned curing units. This effect is attributed to the properties of radiation emitted by the laser. The radiation possesses a small extent wavelength range (±5 nm) located quite close to the absorption maximum of camphorquinone [4] and the radiation has a high photon density. Unlike the halogen and the LED lamp curing technologies, these special properties of a blue diode laser lead to an efficient activation of the photoinitiator and thus to an efficient curing of the composite [40] despite a low power output setting.

The results also show that there is no clinically relevant increase in the curing depth by varying the laser output power up to a certain level. This result is explained by the fact that the curing depth depends on the penetration depth of the radiation in the composite [41]. The photoinitiator is activated and the subsequent polymerization reaction is triggered merely when one photon strikes the photoinitiator molecule [42]. With the high power output setting of 2 W, no significant upper curing depth was achieved compared to the power output setting of 1 W. Consequently, a high power output setting does not lead to a deeper penetration of the radiation in the composite. Thus, the power output up to a certain level is not a useful parameter

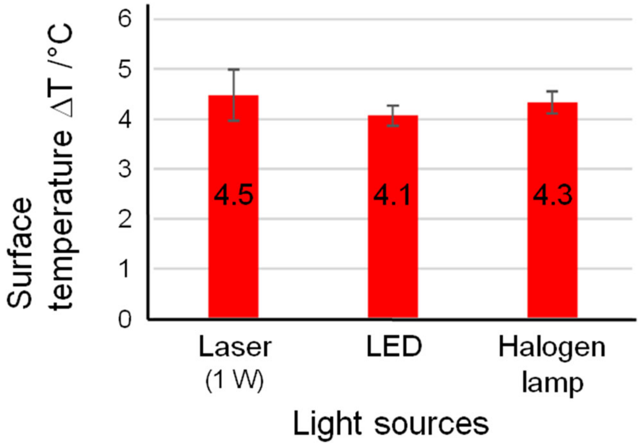

Fig. 4 Temperature increase (ΔT) on the surface of the composite resin, occurred by curing the composite resin with the corresponding light curing units. Laser power of 1 W was selected for this measurement. ΔT determined is comparable for all light sources

to affect the curing depth. However the extent to which different laser output powers influence the mechanical properties, e.g., the conversion rate of the polymerized composite was not analyzed.

The measured curing depths concur with the results of the study by Rueggeberg et al. [27]. They used a similar experimental setup for their investigations; noteworthy is that the diode laser employed here is also comparable to the light curing units used in their investigations.

The findings of the surface temperature measurements show no significant differences among the three light sources for the photopolymerization. The temperature increase was caused by the emitted radiation of the light curing source and the following polymerization reaction [43]. All temperature increases were below the value of 5.5 °C and thus the thermal stress to the pulp would not be critical in a clinical setting [22].

Furthermore, the temperature increase in the ground area measurements showed no significant differences among the laser (1 W), the halogen, and the LED curing units; temperatures below 5.5 °C were attained [22].

Reducing the laser beam diameter (∅ = 8 mm → ∅ = 1.8 mm) led to a significant increase in temperature (ΔT = 5.4 °C) even though the laser output setting (1 W) remained constant. The adjustment of the laser beam diameter caused a decrease in the spot diameter and an increase in the photon density. Consequently, this increase results in a more efficient activation of the photoinitiator and a stronger polymerization reaction. The stronger polymerization reaction and the direct increase of the intensity are the reasons for the temperature increase of 5.4 ± 0.6 °C. This result shows the necessity to test modifications of the parameter settings in vitro to protect the pulp tissue from thermal stress.

In this present study, basic polymerization parameters as curing depth and temperature measurements indicate that equivalent results can be generated compared to halogen and LED-sources. However, in current adhesive dentistry, the polymerization process implies further parameters to manipulate resin curing in different clinical applications.

A sufficient conversion of the material has to be guaranteed without harmful heat generation. Furthermore, the dynamics of polymerization shrinkage (curing time) needs to be controlled to avoid leakage. By varying the laser settings, e.g., using the pulse mode and modifying the average power by changing pulse energy, pulse repetition rate or duty cycle, this advanced laser technology enables the clinician to simply optimize the adhesive quality and resin curing. Sound parameters for different clinical applications, e.g., adhesive cementation of ceramic restorations, need to be identified in future studies. Therefore, the presented laser technology already offers expansive setting options.

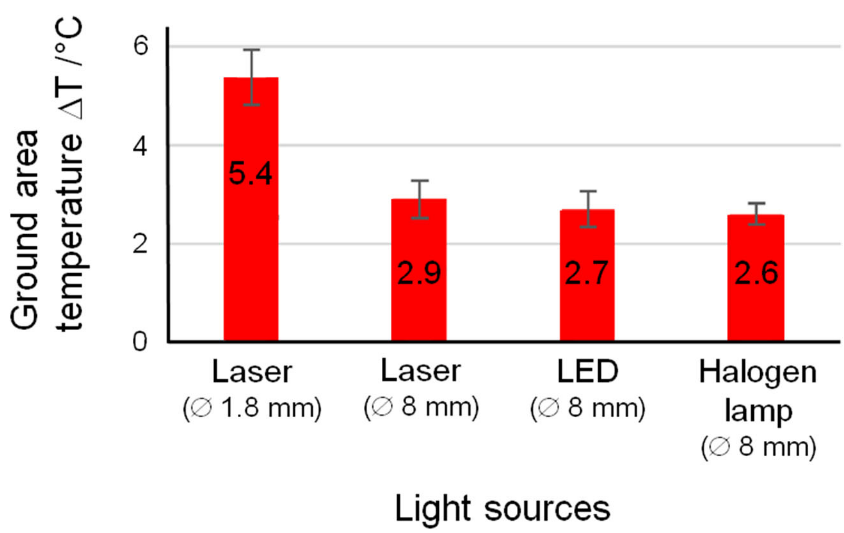

Fig. 5 Temperature increase (ΔT) of the ground area measured in a 6 mm deep cavity. A laser power of 1 W was chosen. For the same beam diameter (8 mm) all light sources show comparable results for ΔT. At an increase of the intensity (reduction of the beam diameter down to 1.8 mm) the laser shows a corresponding temperature increase (approximately by a factor of 2) on the ground area

Outlook

The biggest advantage of the blue diode laser unit is its special radiation characteristics: The high photon density and the sharply limited wavelength range combined with the thin flexible quartz glass fiber open up new possibilities for the photopolymerization of composite resins for complex restorations [44], root canals [18] and for tunnel prepared teeth [45].

The possibility to polymerize composite resins by using a blue diode laser allows clinicians now to extend the range of applications of this novel light source. Therefore, this diode laser can be recommended as a promising polymerization device that accomplishes new requirements of adhesive dentistry. In this context, the effects on other resin types need to be explored in the future.

Conclusion

This investigation has shown that the new diode laser, emitting blue light of 445 nm wavelength, yields comparable results to those of halogen lamp and LED technology in terms of curing depth and temperature response. Based on its wide range of adjustable irradiation parameters, this laser technology can be properly adapted to the properties of the restorative materials used in clinical practice. Thus, the blue diode laser will advance the state of the art of photopolymerization of composite resins in restorative dentistry.

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Compliance with ethical standards

Materials sciences

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Materials sciences

Informed consent Materials sciences

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