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An analysis on the potential of diode-pumped solid-state lasers for dental materials

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ABSTRACT

Material structure-property relationship is strongly related to the employed process technology. Over the past years, laser processing of engineering materials has been proposed in many fields and different uses for diode lasers have been found in dentistry. In this contest, the potential of GaN- and InGaN-based laser diodes to cure dental materials was analysed. Two wavelengths of 405 nm and 445 nm were used as heat or light sources for warm condensation of gutta-percha, light transmission in dental posts and brackets or light curing of dental composites. Additive manufacturing approach was considered to fabricate 3D root analogues, suitable supports, positioning systems and moulds for optical measurements. A three-axis CAD/CAM system was implemented for positioning and aligning the laser beam.

The ability of diode-pumped solid-state lasers to cure dental materials or to transmit light was compared to that of a traditional instrument. Temperature profile at the apex of an additive manufactured root canal sealed with gutta-percha, light transmission through translucent quartz fiber post or through aesthetic ceramic bracket, bending properties and morphological features of light cured dental composites (Gradia Direct - GC Corporation and Venus Diamond - Heraeus Kulzer) were measured. Results showed a very high potential of diode-pumped solid-state lasers to be used in endodontics, orthodontics and restorative dentistry.

1. Introduction

In the last half century research has shown that dentistry can benefit from laser applications, especially for procedures such as dentin treatment, photodynamic therapy, diagnostics, osteotomy and tooth cavity preparation [1–3]. However, the potential of laser diodes in endodontics, orthodontics and restorative dentistry is not fully exploited.

The success of an endodontic therapy relies on the hermetic sealing of the cervical root canal, and warm condensation of gutta-percha through a temperature-controlled electric heater is the most popular approach for this purpose [4, 5]. Nd:YAG laser, which is used as heating source to soften gutta-percha, provided root sealing ability similar to electric heater based instruments [6], while Argon lasers promoted sealing capability superior than CO_2, and Nd:YAG lasers [7]. In clinical practice, electric heaters are preferred to lasers because they are cheaper and simple to use [6]. However, studies regarding the use of diode-pumped solid-state lasers to heat gutta-percha are missing.

The use of a post to retain a core restoration is recommended for endodontically treated teeth showing an extensive coronal tissue loss [8]. Endodontic posts are made of biocompatible fiber reinforced polymers that mimic the mechanical properties of hard tissues [9–12]. However, these posts are cemented into the root canal, and debonding at the post-cement interface is commonly observed [13]. The capability of translucent post to transmit light [14] and to improve mechanical properties [15] of luting cements cured by conventional light curing units (LCUs) is reported. A drawback of conventional LCUs is the limited light intensity that is possible to transmit through the endodontic post because of the very small diameter [13–15].

On the other hand, orthodontic brackets in conjunction with arch-wires represent the most popular approach to align teeth [16, 17]. Retention capability of brackets on enamel relies on the bonding between orthodontic adhesive and the bracket base [18]. Ceramic brackets have been introduced for aesthetic reason, but it has been suggested that translucency provides another pathway for the light produced by LCU, thus improving the quality of the bonding system based on photocuring [19]. Little is known about the capability of diode laser to bond ceramic bracket onto enamel [20, 21], especially in relation to the transmission of violet light which should promote superior bonding and curing process [19, 22].

Light activated composites and resins represent the most popular choice in the restorative dental practice [23, 24] as these materials, which are used in conjunction with a LCU, allow an on-demand process

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Table 1
Light sources and electric heater used in the current research.

Source	Model	Manufacturer	Wavelength/temperature	Power
Blue laser	BM-200 MW	Sothiclasers	445 nm	200 mW
Violet laser	BM-200 MW	Sothiclasers	405 nm	200 mW
Blue LED	Dental Starlight	Mectron	465 nm	1100 mW/cm^2
Electric heater	System B	Analytic Technology	180 °C	

of polymerization [25, 26]. This approach offers the clinical advantage of extended working time, thus promoting precise material placement. Different LCUs, including lasers, have been investigated for this purpose [27–29]. However, only few investigations regarding the use of blue laser diode for curing restorative composites are available [30–32], and studies on the conventional mechanical properties of dental composites cured with diode-pumped solid-state lasers are missing.

The aim of the current research was to analyse the potential of GaN- and InGaN-based laser diodes in endodontics, orthodontics and restorative dentistry.

2. Materials and methods

Light sources and/or heating systems are reported in Table 1.

Wavelength distribution of the LCUs was measured using a compact spectrometer (350–700 nm, CCS100/M, ThorLabs, Newton, NJ, USA) equipped with FT030 fiber (reinforced Ø3 mm Furcation Tubing, Newton, NJ, USA), CCSAC cosine corrector and ThorLabs OSA software. Optical power of the LCUs were measured using a radiometer (LED, Demetron, Kerr, CA, USA), a compact power, and energy meter console (PM100D, ThorLabs) equipped with a sensor (S121C, ThorLabs), and connected to the PMD100D software running under LabView. k-Type thermocouples connected to National Instruments DAC interface and LabView system were used for temperature measurements. 3D dental root analogues, suitable supports, positioning systems and moulds were fabricated by stereolithography (EnvisionTEC Perfactory 3D Printer) [33], while precise spatial positioning of LCU and heating units was obtained using a 3-axis CAD/CAM system [34]. To evaluate the mechanical properties, three-point bending tests were performed using an Instron 5566 testing machine.

Table 2 reports all the systems and materials used in the current research.

To evaluate the potential of diode-pumped solid-state lasers for endodontic therapy, fifteen acrylic based composites reproducing the root dentine of an instrumented central maxillary incisor having a straight canal [5] were 3D printed together with a base support perpendicular to the root canal axis. Gutta-percha cone was positioned inside the canal, k-type thermocouple was inserted and cemented in the root (Fig. 1a). Samples were randomly divided into three groups, and System B, blue and violet laser diodes, mounted on a 3-axis stepper motor positioning system, were used for warm condensation of gutta-percha. Temperature was recorded at rate of 10 pts/s.

Five DT light posts were used to obtain an intense light transmission for cementing translucent posts by means of diode lasers. Each post underwent three successive light transmission measurements using the Starlight Dental blue LED and the blue and violet lasers for curing the system from the top of the post. An opaque mould, which reproduced the negative shape of the translucent post and contained a hole for positioning the spectrophotometer fiber tip at a depth of 5 mm from the apical region of the post, and a round base to fit in the sensor of the wattmeter, was 3D printed (Fig. 1b). Light power and wave spectra were properly acquired.

To investigate the potential of diode-pumped solid-state lasers to bond aesthetic bracket, using the translucency of ceramics as the only pathway, five Transcend brackets were used. Each bracket underwent three repetitive light transmission measurements using the Starlight Dental Blue LED and the blue and violet laser diodes for curing the system from the top of the bracket. An opaque mould reproducing the negative shape of the bracket base, incorporating a round bottom base to fit in the sensor of the wattmeter, and lateral walls to optically shade light around the bracket, was 3D printed (Fig. 1c). Power data were acquired as a function of the distance between the light source and the bracket top surface.

Fifteen disposal acrylic open moulds were 3D printed (Fig. 1d) to evaluate the capability of diode-pumped solid-state lasers to cure composite materials for restorative dentistry. Each mould presented a straight slot with thickness, width and length of 1 mm, 1 mm and 25 mm, respectively. Each slot was filled with a dental composite (Gradia Direct - GC Corporation and Venus Diamond - Heraeus Kulzer), which uses blue light and camphorquinone/amine initiator system. A mylar strip was positioned on the top of the mould, and a load of 25 N was distributed on the top of the specimen to obtain a flat surface. The photopolymerization was carried out on three samples, each consisting of five specimens, according to the light source (Starlight Dental Blue LED and the blue and violet laser diodes). Each source illuminated the material from the top of the mould. To polymerize each specimen along the whole length, each LCU was mounted on the three-axis CAD/CAM system, and the light source was moved along the specimen length direction at a speed of 0.625 mm/s, thus achieving the polymerization in 40 s. Specimens were kept in dark environment for 7 days before performing three-point bending tests at a speed of 1 mm/min using a span of 20 mm [29]. Young's modulus and strength were evaluated according to ASTM D 790.

To compare the obtained data, ANOVA with Bonferroni post-hoc test was used. Values of $p < 0.05$ were considered to be significant.

Scanning electron microscopy (SEM) was also performed using a FEI Quanta FEG 200 apparatus (The Netherlands), in order to analyse the fracture surfaces.

3. Results and discussion

The structure-property relationship plays a crucial role in designing advanced materials. The technology process clearly affects the material structure and properties, thus influencing the final application. Laser processing of engineering materials have been widely studied in different fields and, in particular, many uses for diode lasers have been found in dentistry.

Even though it has been reported that laser curing can improve the

Table 2
Analysed systems: type, manufacturer, organic matrix and inorganic phase.

System	Type	Manufacturer	Organic matrix	Inorganic phase
Gutta-percha	ISO/pink	Dentsply	Gutta-percha	Zinc oxide, Barium sulphate
Post	DT light	Dentsply	Epoxy resin	Quartz fibers
Bracket	Transcend 6000	3 M Unitek	–	Polycrystalline alumina
Micro-hybrid composite	Gradia Direct	GC Corporation	UDMA, DMA	Fluoro-alumino-silicate glass, Silica
Nano-hybrid composite	Venus Diamond	Heraeus Kulzer	TCD-DI-HEA, UDMA	Barium aluminum fluoride glass

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