Insights into blue lasers for photopolymerization

© Emeritus Professor Laurence J Walsh AO

The concept of using a laser for photopolymerisation of light cured dental materials has been around for more than 3 decades [1]. During that time there has been a dramatic transition from large argon ion gas lasers running on three-phase mains electrical power through to handheld battery-powered semiconductor diode lasers, with the change in physical size being matched by a reduction in complexity, and in price, along with greatly enhanced portability (Fig. 1, Table 1).

Blue light emitting diode lasers can undertake all the known functions of traditional LED or halogen dental curing lights [2], and can offer short curing times like those previously used with plasma arc (PAC) lamps, but with greater effectiveness.

Understanding the technology

The argon ion gas laser was the first system used for light curing in dentistry. This laser type produces two major wavelengths, 488 nm in the visible blue range, which is suitable for activating camphoroquinone, as well as 514.5 nm in the visible green range, with the ability to choose between the two. In some argon ion laser systems, it was also possible to choose the laser emission line of 458 nm. Argon ion lasers have been used extensively in ophthalmic surgery for many years, and medical laser systems were adopted for use in dental practice in the early 1990s. A handful of systems of this type remain in operation in dental clinics in Australia.

Argon ion gas lasers have a low electrical conversion efficiency, meaning that most of the incoming power from the three-phase mains electrical supply is converted into heat, which requires the system to have a large water and/or air cooling system. This makes argon ion lasers very large and heavy units, and also requires the dental practice to have a three-phase power outlet installed to service the high current demands of the laser system [3]. Similar comments apply to helium-cadmium lasers which emit light at 441.6 nm, however these were never produced commercially for dental applications. There was also passing interest in diode pumped solid state (DPSS) lasers emitting light at 473 nm, however these are large units with flashlamps and water cooling that also need a mains power supply. They were never adopted into dental practice for light curing.

The advent of blue light semiconductor diode lasers in the 1990s by Nakamura working at Nichia in Japan has considerably simplify the technology for generating visible blue light. Low-power versions of these same diode lasers are used today in a wide range of industrial and consumer devices, including Blu-ray™ players. Such lasers are now used widely in displays, lighting, welding, and optical processing, as well as in medical lasers.

Blue light diode lasers are typically constructed using deposited layers of gallium nitride (GaN) or indium gallium nitride (InGaN), with the latter being particularly efficient for generating light in the 445-465 nm range, which is useful for photopolymerization. The typical wavelength of GaN diode lasers is 450 nm, which makes these ideal for activating traditional and novel photo-initiating agents.

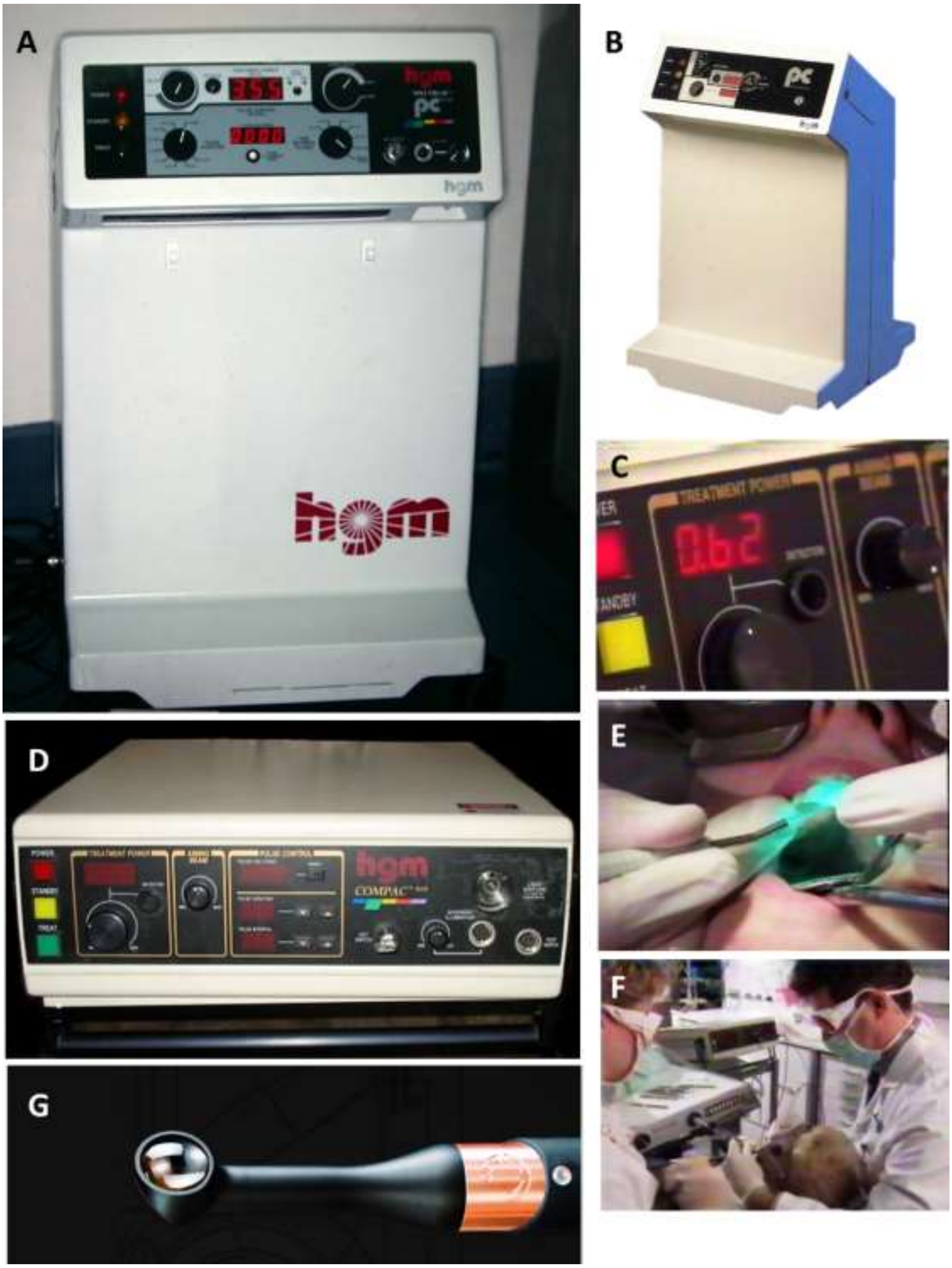

Fig. 1. Laser sources for blue light curing used by the author, showing the considerable progress in the technology over 30 years. Panels A-C: HGM PC argon ion laser (1991), Panels D-F: HGM Compac argon ion laser (1993). Both these models had an output power of 4 watts and were large and heavy, and required three-phase electrical power. Panel G: Monet battery-powered handheld GaN semiconductor diode laser (2023). Note the laser protective eyewear on the patient and staff members in panel F.

Table 1. A comparison of dental blue light curing systems

Parameter	LED	Halogen	Argon ion laser	Blue diode laser
Size and weight	small	medium	large	small
Power source	battery	mains	mains	battery
Primary wavelength	460 nm	470 nm	488 nm	450 nm
Spectral bandwidth	50 nm	100 nm	1 nm	5 nm
Conversion efficiency	33%	2%	0.1%	35%
Beam collimation	variable	low	low	high
Cooling system	fan or passive	fan	water and air	passive

In recent years, single GaN emitters capable of optical outputs of up to 8 watts in continuous wave mode at 442 nm have been described [4,5]. Typical drive voltages for such components are between 4 and 6 V DC, with threshold current values in the order of 100 mA and maximum current flows up to 5 amperes, making them ideally suited for operation from lithium ion batteries and other low-voltage power sources. Today most blue light semiconductor diode laser components are made in either Japan or in Poland, which are the two countries where much of the blue diode laser technology has been developed over the past 30 years.

Self-heating is an issue with GaN semiconductor diode lasers, and this can affect their performance when used in continuous wave mode. With their electrical conversion efficiency being around 35%, a diode laser which is emitting 2 watts of light (optical power) will be producing about 4 watts of heat. If uncontrolled heating occurs during prolonged use, this can lead to catastrophic optical damage (COD) within the diode laser [5,6]. Fortunately, this scenario will not occur in dentistry because only short bursts are needed for curing, in the order of 1-3 seconds per burst.

Optical delivery system

Being a point light source, the optical arrangement from a GaN diode laser allows a low divergence near parallel beam to be created which is optically homogeneous. As shown in Figure 2, with the Monet™ handheld laser system, the optics create a near parallel slightly diverging beam of approximately 8 mm in diameter. The low divergence means that there is little change in the power density (intensity) at the target as the working distance from the head of the laser to the tooth changes over several centimetres. This is unlike the situation for most curing lights where the beams diverge at larger angles from the head of the curing light tip, and the power density falls away as the distance from the tooth increases, because of the inverse square law. Thus, the near parallel beam of the laser provides a major advantage over conventional curing lights for curing materials in deeper preparations and in posterior regions of the mouth where access is more difficult.

Practical considerations

The first semiconductor diode laser designed for light curing was released into the dental market after gaining US FDA approval in 2021. The Monet™ laser (manufactured in the USA by the CAO Group Inc, and distributed in Australia by BioMeDent) (Fig. 3), is a 2 watt laser that can deliver 2 Joules in just 1 second, at a power density of some 5,303 mW/cm^2. This power density is far greater than that which can be achieved by other curing light sources [7], and is over 8 times the minimum level of 600 mW/cm^2 used as a benchmark for curing lights for the past 30 years. The short exposure times used mean that, with this laser, lower energy doses (in Joules) are needed to achieve adequate photopolymerisation for increments of resin composites up to 2.5 mm in depth. The high depth of cure which can be achieved for such laser systems means that there is a lower differential in hardness for resin composites for hardness of the surface versus hardness at a depth of 2 or 2.5 mm.

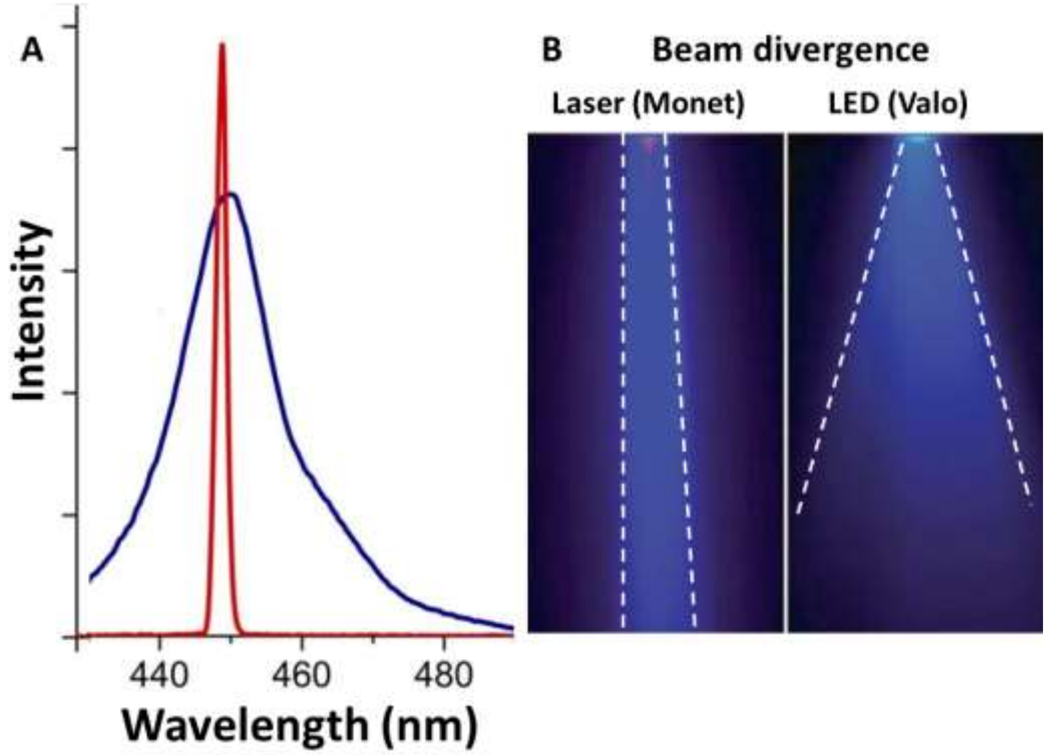

Fig. 2. A comparison of semiconductor diode lasers and high-intensity LED lights for photopolymerization. Panel A: A spectral bandwidth plot showing intensity versus wavelength, for a high-intensity LED light (Ultradent Valo) in dark blue, versus the 450 nm Monet diode laser in red. Panel B shows the beam dispersion from the end of the curing light at the top of each image. Note the very small divergence for the laser, and the much wider divergence for the LED light. This difference comes about because the laser is a point source of light and can be readily lensed to give a near parallel beam.

Fig. 3. The major components of the Monet™ diode laser dental curing system. The main laser unit with its rechargeable battery attached is shown in panel B. A single pushbutton operates the laser. A set of 3 beam width reducing apertures and the 50% neutral density filter are shown in panel A. Laser protective eyewear is shown in panel C, and the laser protective handheld paddle shield in panel D. The replaceable battery is shown in panel F, and the battery charging base and stand for the laser in panel E. The base also contains a power meter to check for the proper operation of the laser.

Performance

A slight change in clinical approach is needed with diode laser curing, since repeated short bursts are used, rather than longer irradiation periods. A single 1 second cure is suitable for curing bonding agents, while when layering resin composite materials, a single 1 second cure per layer is the normal approach. The surface of the resin will be hard to the touch after this 1 second period.

With any light source, the depth of penetration through various dental restorative materials is influenced by the presence of the various pigments which are used to create the unique shade of the material. A restorative material which has a more intense yellow colour will attenuate blue light more because of absorption. Longer or repeated exposures give enhanced depth of cure because of greater radiant exposure. This is why repeated bursts with longer 3 second exposures are preferred with this laser system, especially when bulk fill resin composites materials are being cured [8]. The Monet 450 nm laser curing system has been tested with over 50 brands of light cured dental materials, and has been shown to polymerise all of these [13-15].

The depth of cure which is achieved varies according to the brand of resin composite and the shade, as well as the curing time used with the laser. As light passes through dental materials, light from a laser penetrates more than light from an LED of a similar wavelength, because the laser beam is both coherent and monochromatic. This means there is less destructive interference as scattering events occur within the material. The laser manufacturer (CAO Group Inc, Utah, USA) has provided a series of reference graphs [9] showing the curing depth of various common resin composite materials, as measured using the ISO 4049:2019 standard.

Another way of easily determining the influence of the laser for light curing is that a 1 second laser exposure gives the same effect as a 10 second cure with a standard LED curing light, and 3 seconds is directly comparable to 20 seconds with an LED curing light [8]. A clinician can also do a practical test themselves, by directly exposing the end of a syringe of resin composites material to the laser, and then extruding the set material from the syringe and determining how far the setting reaction has progressed by assessing the hardness of the extruded composite with a probe. This simple practical test is the basis of the ISO standard, and is a useful technique when planning to laser cure the material in a situation where there is no previous data at hand.

Safety for the dental pulp

The short exposure times used with diode laser systems minimise the extent of thermal stress to the dental pulp. Because of the high efficiency of monomer conversion under the intense photon flux generated by laser irradiation, the light dose required for curing is less than for conventional light sources, and less heat is generated within the bulk of the composite material itself during the period of irradiation [10,11].

A useful clinical approach is to cure restorations in separate bursts of 1 second duration, bearing in mind that each separate exposure represents the curing period for approximately 2.5 mm of material. A gap in time between each of the exposures will reduce heat accumulation [12]. For very large restorations that are being placed (e.g. complete coronal buildups larger than 8 mm in diameter) it is appropriate to do to laser curing procedures with overlapping spots.

A modified irradiation protocol is used when curing resin cements beneath zirconia crowns, with a 1 second cure beneath each cusp for a molar crown, which is repeated 3 times. Following the same approach, three curing cycles of 1 second each can be used with resin cements beneath veneers on anterior teeth. The extremely high power density of the laser means that penetration through translucent materials can be reliably achieved. This includes through various ceramic materials when the target to be cured is a resin cement beneath a veneer or a crown.

It has been estimated from laboratory tests that a continuous (uninterrupted) exposure period of more than 5 seconds (well beyond the manufacturer's recommended exposure time) would be needed to approach the threshold of 5.5°C at which thermal stress to the dental pulp becomes significant [13]. One must also bear in mind that the temperature measured on the very top surface of a restoration will be higher with laser curing then when an LED is used, simply because of the greater power density of the light, and the accelerated polymerisation reaction which is occurring on the top surface. This helps to achieve greater conversion of the resin and to increase its hardness. Nevertheless, the thermal stress at the level of the dental pulp will still be tolerable despite the warmer surface, due to the poor heat conduction of the material.

Safety for the soft tissues

Intense visible blue light is strongly absorbed into haemoglobin [3]. Consequently, it is important to avoid inadvertent exposure of gingival tissues when curing buccal or cervical restorations. To make this easy to do, a sized aperture can be applied over the laser tip to reduce the spot size down from the normal 8 mm to 6, 4 or 2 mm. Applying an aperture does not influence the divergence of the beam as it emanates through the aperture opening. The manufacturer also makes available a neutral density attenuator which will reduce the beam intensity by 50%. This is intended primarily for use when doing tack curing of veneers, rather than for procedures near soft tissues.

Safety for staff and patients

A consequence of the low beam divergence of the Monet system beam is that the nominal ocular hazard distance (the distance within which laser protective eyewear must be worn) is quite high, at almost 10 metres. In practical terms, this means that the patient and everyone working in the dental operatory will fall within the nominal ocular hazard distance of the laser. Patients and staff need to wear suitable laser protective eyewear (e.g. optical density above 8) which attenuates the laser wavelength to below the level which can cause retinal damage to the eye (Fig. 3).

There is also a paddle filter available which also has a high optical density (OD of greater than 4) for additional use, as well as inserts that can be worn between the eye and magnifying loupes. Another option used by the author is a protective laser face shield, as this allows normal loupes to be worn beneath this [16].

When compliance with wearing laser protective eyewear is excellent, staff can work with complete confidence and safety. After more than 30 years of using lasers for curing (Figure 1 Panel F), there have been no adverse events reported in the literature, which is a testament to the performance of the protective eyewear as well as to the training and clinical skill of those who have been doing laser curing over the past 3 decades.

The regulatory requirements for laser safety in a healthcare setting are outlined in Australian standard AS 4173:2018 Safe use of lasers and intense light sources in health care. This standard provides the platform for safety measures in those 3 jurisdictions within Australia (Queensland, Western Australia, Tasmania) where there is formal regulation of laser safety in dental practice.

Since the Monet laser is manufactured in the United States, like other lasers of US origin, it is shipped with a US laser safety sign. This sign does not meet the Australian requirements, being red on black, instead of black on yellow. Clinics can create their own signage (e.g. by laser printing the required information onto yellow paper and then eliminating this) as long as they meet the requirements for specified wording on the laser sign (indicating that a Class 4 visible laser is in use).

Information on laser safety requirements for the Australian setting can be obtained from online courses such as those presented by the author. Information on laser regulation is summarised in the ADA Practical Guide on Lasers. Extensive information on the processes for properly installing and commissioning a class 4 laser in an Australian dental practice can be obtained from the Australian Association for Laser Dentistry for those clinicians who are members of this association (aald.asn.au).

Conclusions

Since its release in North America in 2021, the Monet handheld diode laser curing system has attracted great interest. Many studies on blue laser photopolymerisation have shown positive results [10-15, 19-28], extending the literature from what had been done with previous generation blue light argon ion lasers. In both cases, the high power density of the laser light has been shown to improve the physical and mechanical properties of resin composite materials.

Moreover, over recent years there have been important advances in the literature regarding the behaviour of contemporary resin composites materials during light curing, especially those materials used for bulk filling when exposed to bursts of high intensity light [29-36]. This sizeable literature shows that contemporary materials can be cured successfully using short bursts of intense light, provided that the exposure conditions are optimised to align with the properties of the relevant material. This reinforces the need to access the manufacturer's guide and also to perform a test cure (such as the syringe test mentioned previously) to confirm the correct number and length of irradiation cycles with the laser.

Many major dental innovations require almost a generation for a change to become completely embedded in everyday clinical practice. LED curing lights were introduced in 2001, and now well over 20 years later it would be unusual to find a dental practice that was not using an LED light for photopolymerisation. Driving the change from halogen lamps to LEDs was the greater reliability and performance of LEDs over halogen lamps, and a reduction in the length of the curing time. Exactly the same issues are relevant now when considering the transition from an LED curing light to a diode laser curing system, with enhanced performance and reduced clinical time being the major benefits. The question is whether this revolution will occur as quickly as the transition to LED curing, and only time will tell.

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