Critical Review
Dental Materials/Dentistry

Light curing in dentistry and clinical implications: a literature review

Frederick Allen RUEGGEBERG[a]
Marcelo GIANNINI[b]
Cesar Augusto Galvão ARRAIS[c]
Richard Bengt Thomas PRICE[d]

[a]Augusta University, Dental College of Georgia, Department of Restorative Sciences, Augusta, GA, United States of America.

[b]Universidade Estadual de Campinas – Unicamp, Piracicaba Dental School, Department of Restorative Dentistry, Piracicaba, SP, Brazil

[c]Universidade Estadual de Ponta Grossa – UEPG, Department of Restorative Dentistry, Ponta Grossa, PR, Brazil

[d]Dalhousie University, Faculty of Dentistry, Department of Dental Clinical Sciences, Halifax, NS, Canada

Declaration of Interests: The authors certify that they have no commercial or associative interest that represents a conflict of interest in connection with the manuscript.

Corresponding Author:
Marcelo Giannini
E-mail: giannini@fop.unicamp.br

http://doi.org/10.1590/1807-3107BOR-2017.vol31.0061

Submitted: May 14, 2017
Accepted for publication: May 22, 2017
Last revision: May 29, 2017

Abstract: Contemporary dentistry literally cannot be performed without use of resin-based restorative materials. With the success of bonding resin materials to tooth structures, an even wider scope of clinical applications has arisen for these lines of products. Understanding of the basic events occurring in any dental polymerization mechanism, regardless of the mode of activating the process, will allow clinicians to both better appreciate the tremendous improvements that have been made over the years, and will also provide valuable information on differences among strategies manufacturers use to optimize product performance, as well as factors under the control of the clinician, whereby they can influence the long-term outcome of their restorative procedures.

Keywords: Polymerization; Light; Curing Lights, Dental; Photoinitiators, Dental; Dental Restoration, Permanent.

Polymerization

In dentistry almost the entire gamut of resin-based restorative products use the same basic monomer family and polymerization mechanism: methacrylates and vinyl, free radical addition polymerization.[1]

Vinyl-free radical methacrylate polymerization

The term "vinyl" refers to the presence of an electron-rich, carbon-to-carbon double bond appearing at the terminal end of a monomer molecule. Specifically, methacrylates are distinguished by the presence of a methyl group covalently bond to the "α" carbon atom. The basic structure of a methacrylate-based monomer is presented in the Figure 1, where the "R" symbol indicates a wide variety of substitution groups that can be added to provide monomers with unique properties.

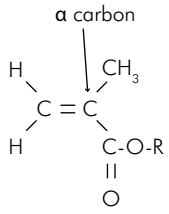

Figure 1. Chemical structure of a methacrylate-based monomer.

In this figure, substitution of the "R" with a methyl group provides the monomer methyl methacrylate, use of an ethyl group yields "ethyl methacrylate", a component in some temporary restorative resins, and placement of a "hydroxyethyl" generates hydroxyethyl methacrylate (HEMA). Substitution with other species that also contain an additional methacrylate group on the other monomer end, provides what are known as "dimethacrylate" monomers: Bis-GMA, TEGDMA, UDMA, etc.

Creation of radicals

The methacrylate vinyl group can be conceived of as a "compressed spring" awaiting release of its constrained, internal energy, which will subsequently be used to link together (polymerize) other such methacrylate groups present in the restorative material. The key to starting the unlocking of this internal energy is creation of a very reactive chemical species that aggressively seeks a high-density electron location (the carbon double bond). The free radical generator is such a species. Different types of chemicals are used for this role, but the end result is similar: the compound is acted upon by some external form of energy (heat, chemicals, or radiant energy), and becomes "activated." This process is shown diagrammatically in the Figure 2.

Once in this form, the species becomes a "free radical," having an outer shell electron actively seeking another electron to share its orbital, thus forming a stable, covalent bond. The clinician should note that it is this step that he/she uses to control when and how fast, and to what extent the polymerization reaction will proceed. It is the number of free radicals formed, the rate at which they are formed, and the rate at which they are annihilated that controls the subsequent polymerization reaction. Thus, factors such as component proportioning, temperature, and amount of radiant energy exposure are under the control of the clinician, and will all significantly influence the rate at which the polymerization process will proceed.

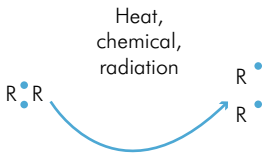

Figure 2. Schematic illustration of external energy factors acting on a radical-generating species to result in formation of "free radicals".

Initiation of the polymerization process

Once created, the freshly formed free radical diffuses through the resin medium in search of a highly electron-rich area, which happens to be the carbon-to-carbon double bond of a methacrylate-based monomer. When these two species collide, the resulting effect is the initiation of polymerization, and is displayed in the following diagram (Figure 3).

In this process, the free radical takes one electron from the 4 contributing to the carbon double bond, and forms a covalent bond between itself, and one carbon atom. In addition, the now extra electron between the carbons atoms moves to a different shell, leaving behind a single covalent bond between the two carbon atoms, where a double bond occupied this space before. Now, the extra electron in the outermost carbon atom becomes the free radical species, and actively diffuses through the low viscosity resin medium in search of another electron-rich, carbon double bond with which to react, in a similar manner.

Chain propagation

The first monomer turned free radical then seeks other electron-rich monomeric species, with which it reacts to form covalent bonds (building the developing polymer network), and also subsequently creates a new radical end for every monomer unit that is joined. This process is presented diagrammatically in the Figure 4.

In this manner, the polymer chain grows in length, by covalently adding monomer units one at a time. As the process continues, the rate of monomer consumption drastically increases, resulting in a very

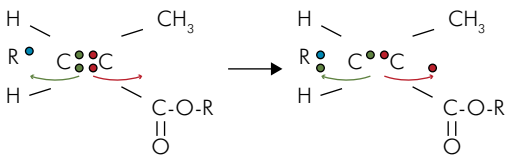

Figure 3. Diagram of the polymerization initiation step.

sharp spike in the rate of the overall polymerization process (termed "auto-acceleration"). With increasing incorporation of monomer into the growing polymer network, the viscosity of the resin system increases, and the rate of diffusion of growing radical ends is greatly decreased, causing an overall lowering in the rate of polymerization, as well as depletion of available, unreacted monomer.

Termination

The polymerization reaction can stop for a number of different reasons. The concentration of available monomer decreases as the reaction progresses, and the growing radical chains have an ever-increasing difficulty in diffusing through the initially gel like and then glass-like resin matrix. However, the most easily understood mechanism is the scenario when two growing radical ends collide. This results in formation of a covalent bond between them, thus quenching each radical element, bringing further growth of either polymer chain to a halt. This process is presented in the Figure 5, where two radical chains meet to form a covalent bond between them, stopping any further chain growth.

Chemically cured products

Use of resin-based products as restorative materials is not new. The first products utilized for these purposes were based on plant or animal components, and were molded to shape using heat (thermoplastic).[2] However, there was no true production-step polymerization process in their final chemical structure. Polymethyl methacrylate (PMMA) was the first organic polymer used for construction of heat-processed denture base materials. Previous to his material, dentures base materials were made using heat-processed rubber (Vulcanite), ceramics, or swage-formed metals. The ability for clinicians to use PMMA was based upon licenses, and the products were heavily under control of major manufacturers.[2] After World War II, the ability to polymerize methyl methacrylate at room temperature (the co-called, cold-cured, or chemical-cured materials) became available.[3] With this ability, the processing of dentures became much less expensive, and less cumbersome. Early forms of a direct, esthetic restorative material (Sevitron, LD Caulk Company, Milford, DE, USA) used a powder/liquid system.[4] Initial results were good, however, the restoration discolored, wore at a very high rate, and displayed unacceptable leakage at the margins. It was not until advancements in monomer chemistry (Bis-GMA, "Bowen's monomer") and the incorporation of finely ground inorganic filler became available, through efforts of the Paffenbarger Research Center at the National Institutes for Science and Technology, that serious consideration for use of resin-based, direct, esthetic restorative materials became a reality.[5]

To reduce resin viscosity, and thus allow higher filler loading, a functional methacrylate co-monomer (triethylene glycol dimethacrylate [TEGDMA]) was incorporated.[6] This formulation was first introduced

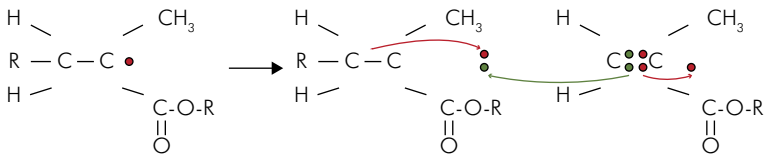

Figure 4. Polymer chain propagation by addition of successive monomer units.

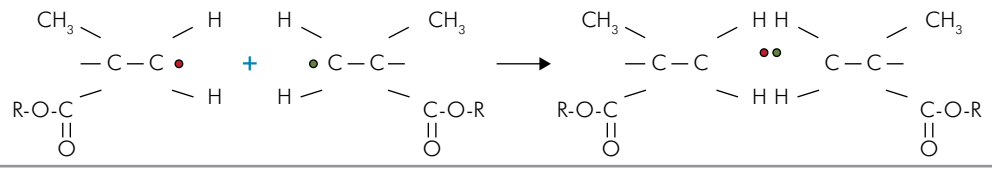

Figure 5. Diagram of chain termination via monomer-radical collision.

to dentistry as a 2-paste, self-curing system named Adaptic (Johnson and Johnson, New Brunswick, NJ, USA) in 1969.[7] The success of these early formulations were greatly improved, with the incorporation of enamel acid etching and use of an unfilled boding resin to micromechanically bond the restoration to peripheral tooth structure.[8] However, the steps needed to physically proportion components, mix them, load the mixture into a transfer device, inject, and hold the material under compression in a matrix material, while the chemical reaction underwent sufficient setting to allow finishing and polishing, took up to 8 minutes, depending on the product.[9] This gave clinicians what they wanted, namely a direct, esthetic restorative material that literally quickly "set on command," when the clinician decided the moment for polymerization was needed.[10]

Dental photocuring

Photoinitiators and electromagnetic spectrum

In order to understand dental photocuring, one must be able to correlate electromagnetic energy contained in light photons with the ability to activate free radicals, via interaction with photoinitiator molecules. A fundamental property of all electromagnetic energy is that it is sinusoidal, and travels at the speed of light. Because of the uniformity of speed, sinusoidal waves traversing a set distance do so using a specific number of complete waves to accomplish that. The number of waves completed per second is referred to as the "frequency" of radiation. The physical length of each completed wave (cycle) is termed its "wavelength." The relationship between electromagnetic frequency and wavelength, corresponding energy levels, as well as correlation with known uses of radiation within specific positions along this spectrum, are provided in the Figure 6.

Ultraviolet-curing

As with most advances in dentistry, the original use of ultraviolet (UV) light to cause polymer curing did not originate in the profession, but instead already existed in the printing industry. In the late 1970's, the LD Caulk company introduced the first dental, UV-cured restorative system. The resin formulation was a urethane-methacrylate based, and the compound absorbing radiant

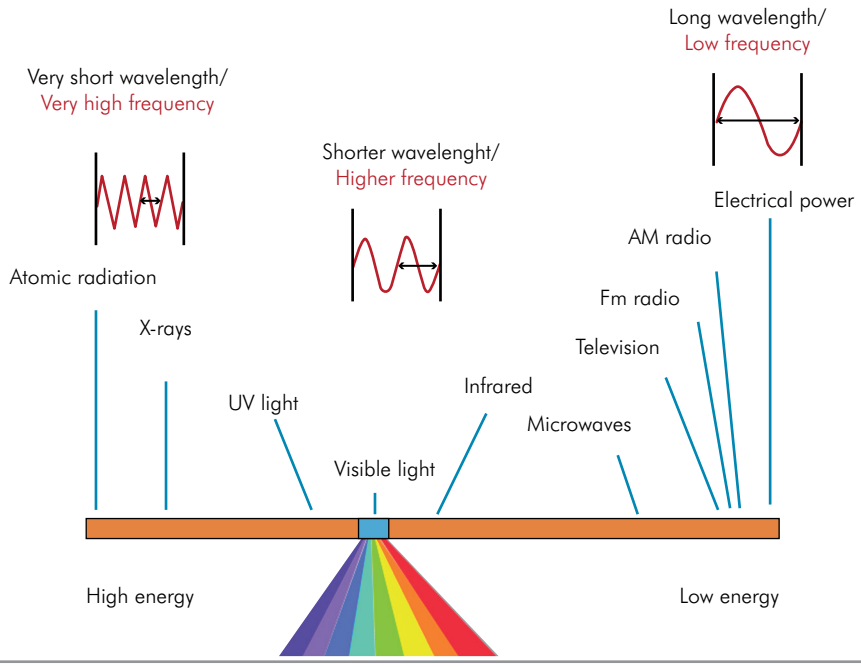

Figure 6. Electromagnetic spectrum with correlated depictions of trends in frequency and wavelength, as well as energy content and location of commonly used band portions.

energy (the photoinitiator) was activated by exposure to electromagnetic radiation at wavelengths around 365 nm. Formulations for sealants as well as filled, direct, esthetic restorative materials were available (NUVA, Dentsply/Caulk, Milford, DE).[11] Despite restorations made using this system lasting many years, problems with lack in incremental thickness placement greater than 1 mm, coupled with the need to expose each increment for 20 to 60 seconds per increment, led to slow adaptation into clinical practice. However, the goal of providing the dentist with a "set-on-command," direct, esthetic restorative material was finally a reality. Light curing units of that time used a UV-emitting source that, unfortunately had to be continually powered, even when not in use, causing decrease in bulb output over time. Additionally, because of the potential for causing cataract formation in the operator, as well as the chance of significantly altering the oral microflora wherever the radiation was directed,[11] radiation limits for dental photopolymerization were restricted to be within that considered as only visible light (380 nm and 700 nm).[12]

Visible light curing

Figure 7 displays the correlation between the wavelength of light in nanometers and the visible spectrum. It is the physical interaction (absorption) of photons at a given wavelength that gives rise to the conversion of visible light into stored energy, later used for creation of free radicals. Within the visible spectrum, absorption of photons involves consumption of their energy and converting that energy into raising an outer shell electron from its regular orbital layer (the ground state) to a higher orbital layer, where it is not usually present (an excited state). Depending on the photoinitiator used, the compound must either react with an intermediary molecule (an amine), which then goes on to form free radicals (a Type 2 initiator), and cause polymerization, or can directly break down into one or more free radicals, which need no such secondary compounds to assist in initiating polymerization (Type 1 compounds). If the excited state does not result in radical formation, the outer shell electron returns to its lower energy state, releases heat, and a lower wavelength photon. Thus, the system will return the same energy of the photon that originally caused absorption and raising it to the higher shell layer. Similar to free radicals resulting from the activation of free radicals formed for chemically cured processes, it is the overall number and rate at which free radicals are formed by this radiant energy that determine the extent to which polymer is formed. In light-cured system, however, formation of free radicals is totally dependent on the presence of photons within the local restorative environment (within a depth) to cause polymerization. This process is unlike chemical curing, where free radicals are formed throughout the bulk of the curing material, regardless of depth.

Dental visible light photoinitiators

Use of photoinitiators requiring visible light for creation of free radicals again arose from other industries. Currently, many different types of photoinitiator systems are used in light-cured, resin-based restorative systems.[13] The most widely used photoinitiator, the camphorquinone (CQ) (1,7,7-trimethylbicyclo[2.2.1] heptane-2,3-dione) Type 2 initiator system (Figure 8), was perfected for dental visible light curing by a project undertaken by Imperial Chemical Industries.[14] This system involves a proton donor/acceptor between a tertiary amine molecule, while CQ is in the excited state. Once this transfer has been made, the amine goes on to form free radical polymerization in the methacrylate resin system: not CQ. Thus, photoinitiation systems incorporating CQ are relatively sluggish, and are less photon-efficient than are the Type 1 systems.[15]

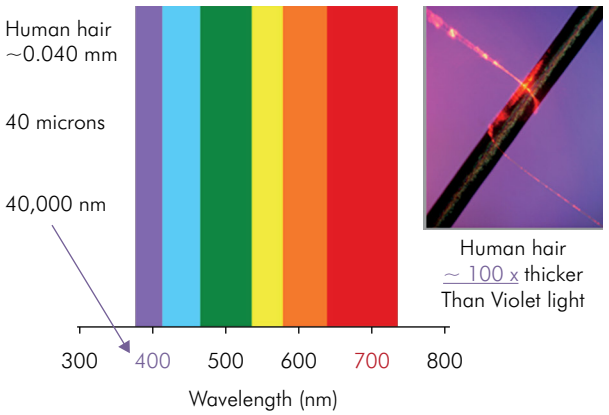

Figure 7. Correlation of wavelength (in nanometers) and human perception of color, as well as perspective of the physical wavelength of violet light.

Camphorquinone is bright canary yellow in color, and only a portion of the content is actually utilized in photocuring of dental systems. Therefore, resulting restorations tend to have a yellowish color.

With the widespread use of vital tooth bleaching in the 1990's, and the ability to raise the color value of enamel past the ability of CQ-based composite systems to provide such light restorative colors, manufacturers searched for methods to either replace CQ totally, or to reduce its concentration and combine it with a synergistic photoinitiator.[16] During the mid 1990's, photo-initiated bonding and composite systems were made available that used only non-CQ containing systems, often referred to as the "alternative photoinitiators." These compounds utilized Type 1 initiators, that had a high absorbency and efficient quantum yields.[17,18] Typical of these compounds was Lucirin® TPO (2,4,6-Trimethylbenzoyldiphenylphosphine oxide). The absorption spectrum of TPO is seen in the Figure 9. Although at one time it was used as the sole initiator, TPO is currently combined with CQ (and other photoinitiators) to provide enhanced resin curing, and decreased restoration yellowing.[16]

A more broad-banded absorbing photoinitiator, having absorption values more into the blue spectral region was also developed. This compound is called "PPD", which stands for 1-phenyl-1,2-propanedione, and is also a Type 2 initiator. The absorption spectrum of this photoinitiator is seen in the Figure 10. This initiator is usually combined with CQ, to result in a synergistic effect, yielding enhanced resin polymerization, while also slowing the overall rate of reaction, and reducing the residual yellow color of the restorative material.[19]

Finally, a new initiator, Ivocerin® (a dibenzoyl germanium derivative), has been developed to provide an even broader spectrum of short wave absorption. This patented product is only available in select products from a single manufacturer (Ivoclar Vivadent). The absorption spectrum of this initiator is seen in the Figure 11. It should be noted that all these photoinitiators have different spectral absorbance ranges of activity, and also differ greatly in their ability to absorb light, as seen in the Figure 12, depicting absorption profiles of all mentioned initiators, but when similar molar concentrations are present.

Visible curing lights

Quartz-tungsten-halogen lights (QTH)

The source in this type unit was not specifically designed for dental use, but instead was adapted from use from the airplane industry, where a durable, long-lasting, high-emission light was required for aircraft body illumination.[20] The first visible-light photopolymerized, direct, esthetic restorative

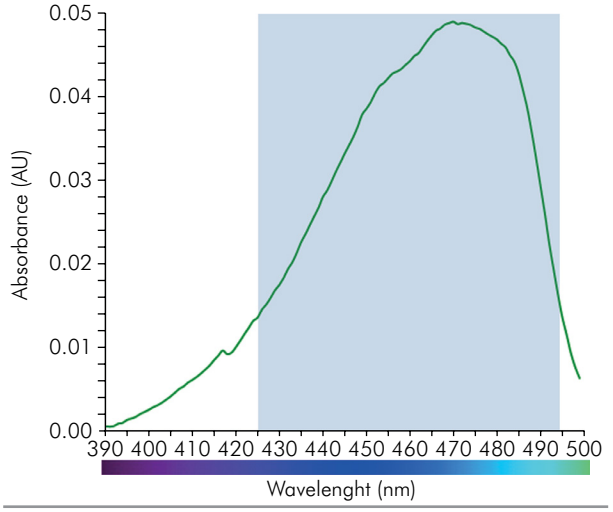

Figure 8. Visible light absorption spectrum of camphorquinone, ranging from about 425 to 495 nm.

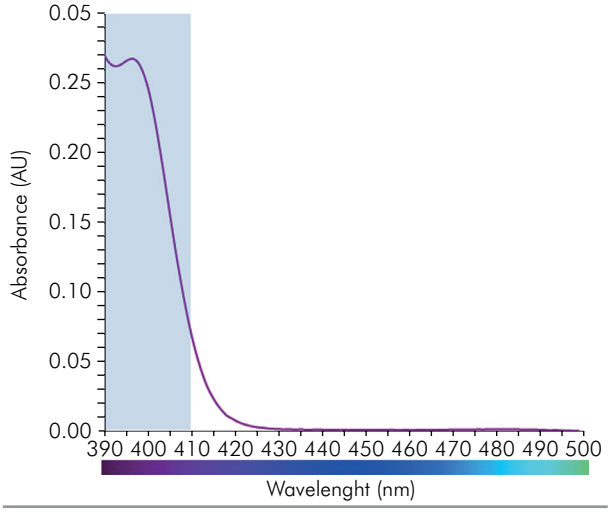

Figure 9. Visible light absorption of the photoinitiator, Lucirin® TPO, spanning from about 390 to 410 nm.

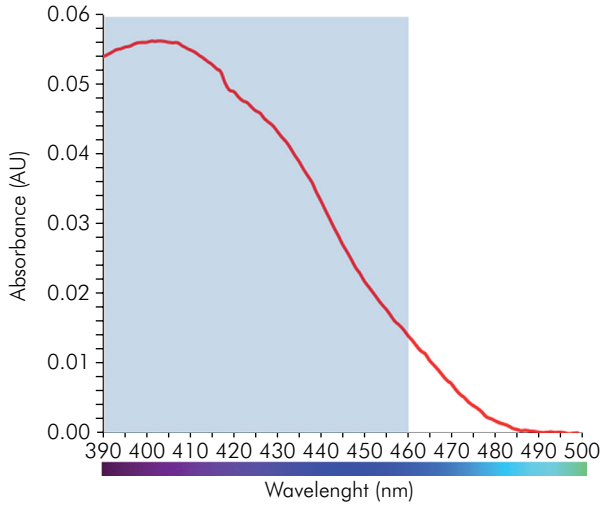

Figure 10. Visible light absorption of PPD, ranging between 390 to 460 nm.

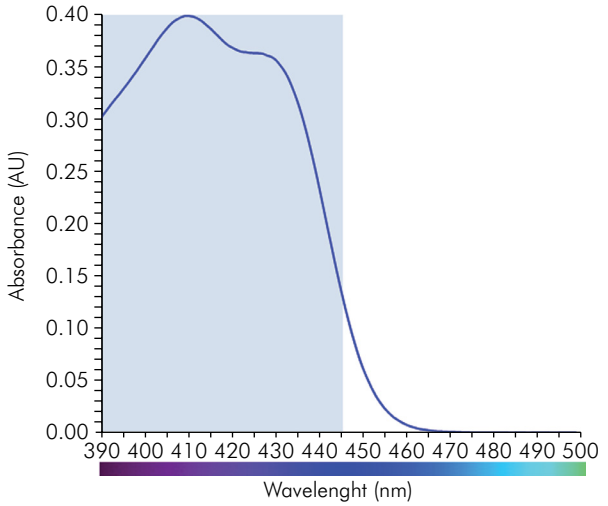

Figure 11. Visible light absorption of Ivocerin® is seen to span from about 390 to 445 nm.

composite was placed in a patient in 1976.[21] The bulb in these units consists of a tungsten filament enclosed in a clear, crystalline quartz casing, filled with a halogen-based gas. As electricity flows through the filament, because of the wire resistance, heat is developed sufficient to cause tungsten atoms to literally vaporize from the wire surface. When this happens, tremendous amounts of electromagnetic energy are released, mostly occurring in the infrared spectral region, where heat in the target is produced. Thus, these types of light units typically require tremendous amounts of filtering to remove that heat, as well as excess visible light not required for photocuring. The form factors of these lights were either hand-held (mostly "gun-like"), having a triggering activation mechanism, and user selectable exposure durations. In such units, the blub itself was encased within the gun, and a fan helped cool the unit, keeping source temperatures to a minimum, while also enabling the halogen cycle to function. In this cycle, the halogen-based gas re-deposits tungsten atoms from the inside surface of the peripheral quartz envelope wall back onto the tungsten filament. A QTH bulb within a hand-held curing gun is seen in Figure 13. The cooling fan is seen to the right, and infrared and visible light filters are housed in the cone section to the left.

Other styles of lights contained a higher power bub within a table top unit, and directed light to the tooth via a long, flexible fiber optic cable. Typical of

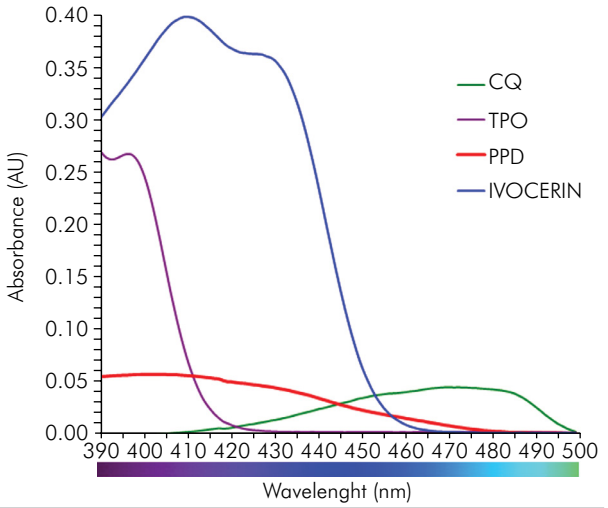

Figure 12. Differences in spectral absorption profiles and absolute absorption values among the dental photoinitiators, when present at similar molar concentrations.

this time, exposure durations for adequately photo-polymerizing a 2-mm thick composite increment ranged between 40 and 60 seconds. A unique feature of the hand-held QTH units was incorporation of hard, non-flexible, removable fiber optic light guides.[22] Guides of different diameters and curvatures could be kinematically inserted and rotated within the receptor port at the distal end of the gun, to provide a wide variety of area coverage patterns, and enhanced abilities to reach specific types of clinical locations. Examples of such types of tips are seen in the Figure 14.

Figure 13. Internal components of a typical QTH curing light.

Figure 14. Different styles of removable fiberoptic light guides used in QTH lights.

During the era when higher output lights were challenging the QTH products (*e.g.*, the PAC units, offering very short exposure times), modifications of the light guides were made to increase the irradiance delivered to the target. One method of accomplishing this goal was use of a "turbo-tip." This device consists of a hard, glass-fibered bundle light guide where the proximal diameter (closest to the hand gun) is larger than that of the distal (closest to the target) end. In so doing, because similar levels of power were available at both ends, but the area over which the power at the distal end was much smaller than that of the proximal end, a greater irradiance (power/unit area - mW/cm^2) value was achieved. However, in so doing, because of the small optical tip diameter, use of this type guide now required the operator to deliver multiple, overlapping exposures, in order to adequately expose all areas of a restoration. In addition, the enhanced output of this type tip was only realized within a short distance from the tip: thereafter, less irradiance was seen, compared to use of a conventional guide, because of the broadened beam divergence of the turbo tip.[23]

In a last effort to match irradiance levels, and thus the short exposure times common using PAC lights, some QTH models incorporated a "boost" mode. When used in this mode, a higher voltage value was applied to the bulb filament, causing it to burn hotter, and emit more light. Use of this mode, accompanied with a turbo tip, was the best effort that QTH lights could make to compete with the ever-increasing PAC market.[20]

Because of the "fast-curing" of high intensity lights of this time, clinicians expressed concerns about the degradative effects of rapid polymerization on development of high internal stress values causing marginal gaps, as well as the potential for increased temperature values to result in iatrogenic pulp and gingival tissue damage.[21] Concepts of photocuring actually underwent a one hundred and eighty degree turn, because of these issues, and QTH units became available with "soft start" features. The idea here was to try and slow the rate of polymer curing, and allow some flow of the unbonded restoration surfaces that would relieve the internal stresses within the restoration. Many types of soft start features termed the "step" and "ramp" modes were incorporated, where initial levels of light during an exposure were either a continuous low value for a short time, after which full output was applied, or the initial phase of the exposure applied a time-based, increase in intensity, until full value was reached, after which that value was held until the light shot off. One additional option included a distinct time delay (from 5 to 10 minutes) between initial application of a low intensity, short duration exposure (200 mW/cm^2 for 3 seconds), and subsequent application of full light output for a longer time (500 mW/cm^2 for 30 seconds): the "pulse-delay" technique.[24]

The spectral emission profile of a typical QTH curing light is seen in the Figure 15, along with color-coded wavelength ranges within which specific types of photoinitiators used in light-activated restorative materials are activated. From this figure, it can be seen that the QTH source is considered "broad-banded" in its spectral emission. Thus, it has the

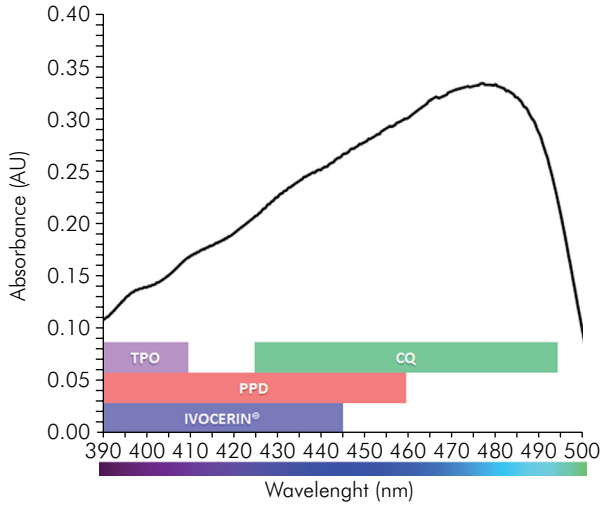

Figure 15. Spectral emission profile of a typical QTH light with absorption wavelength ranges for typical dental photoinitiators.

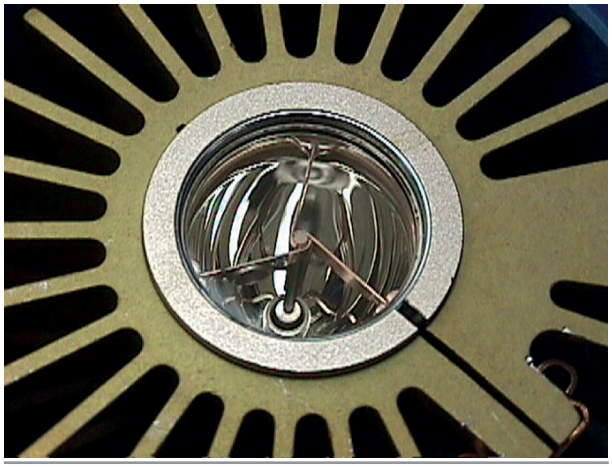

Figure 16. PAC light with associated heat sinking apparatus.

capacity to activate a wide range of photoinitiators that might be present in any type of light-activated dental restorative product. However, the light is quite reactive toward CQ, because it produces many phonons within the spectral region where this initiator has peak absorbance values.

Plasma-arc lights (PAC)

These units utilize two tungsten rods, held at a specified distance, encased in a high-pressure envelope of xenon gas, having a sapphire window through which emitted radiation escapes (Figure 16). When a high voltage is applied across the electrodes, a spark forms, which produces a tremendous amount of electromagnetic radiation over a wide spectral range: from infrared to short wavelength UV. Because of the massive amount of radiation emitted falling outside of the narrow limits needed for dental photocuring, a substantial amount of filtering is required in these lights. Thus, what appears to be a fiber optic light guide transferring light from the source in the table top unit to the intraoral target is really nothing but a 3-foot long optical filter. Inside of this cord is a special liquid that helps to further reduce unwanted IR, UV, and visible light. Without sophisticated electronics, emission from these lights will only be generated during this "spark phase," which lasts for only a few seconds, otherwise permanent damage to the bulb would occur. Early versions of these types of light units utilized this short-lasting spark exposure, and thus they recommended short exposure durations of 3 seconds or less (Figure 17).

However, this duration was not based on the effectiveness of the light being emitted, it was more a factor that, without more expensive, sophisticated electronic control, the unit was only capable of maintaining an output for this amount of time. Many clinicians took these short duration values as being an improvement over the longer times needed for the QTH units, and spoke enthusiastically about the time-savings offered by these types of lights. In addition, during the same time period these early PAC lights were being introduced, vital, intraoral tooth bleaching became a wide spread success. As a result, manufacturers started to utilize the "alternative" photoinitiators that were less chromogenic, and were able to produce composites of high color value, matching that of freshly bleached teeth. The alternative photoinitiators required light of much shorter wavelength than did CQ however. To this end, one manufacturer of early PAC lights provided special "tips" to be used on materials that needed short wavelength radiation (the 430 nm tip) and those that needed blue to polymerize CQ (the 460 nm tip) (Figure 18).

These early PAC lights were also used to enhance the rate at which the peroxide gel broke down intraorally, by exposing it to high intensity visible light. Thus, the manufacturer also included a "bleaching tip," which transmitted over the full spectral range

from 380 to 500 nm. Unfortunately, confusion arose between which type of restorative material needed which wavelength of light to properly photocure. As a result, even though contemporary photocured restorative materials may contain a mixture of photoinitiators, each requiring a specific wavelength band for activation, all materials still contain CQ, which utilized blue light and are most sensitive to light at 468–470 nm. Thus, although optimal light conditions might not be met by specifically matching the spectral emission of a light curing unit with the spectral absorbance needs of a photoinitiator, fairly adequate, but more importantly, deep curing will result with use of the blue component present in every type of contemporary light curing unit.

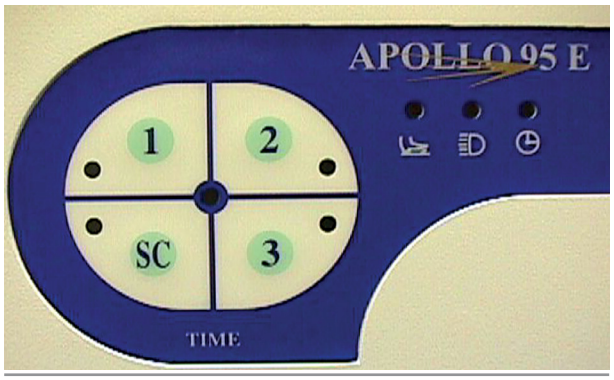

Figure 17. Panel of early PAC light showing options for 1, 2, or 3-second lone exposures.

Figure 18. 430 and 460 nm tips used in early PAC lights.

PAC lights manufactured after these initial models were introduced contained the needed electronic circuitry to maintain the exposure for 60 minutes. Data indicates that, when using these lights, an approximately 10 seconds is needed to adequately photocure a 2-mm thick increment of most composites, but this exposure time does vary depending on the brand and shade of composite. The spectral emission profile of a typical PAC light is seen in the Figure 19. The very broad spectral emission of this type light can be seen to provide high levels of photons to every one of the photoinitiators described so far. Thus, a contemporary PAC light is considered as broad-banded, and users will not have to be concerned about what initiator system exists in any of the restorative materials they use.

Argon-ion lasers

As with the PAC lights, argon-ion lasers were first introduced in Europe. They were introduced in the United States for the purposes of enhancing vital tooth bleaching, but, because the government would not allow their use by anyone else other than a dentist, they also found use for providing light for intraoral curing.[20] These units were large, heavy, and expensive. However, it was not unfeasible to have only a single, large laser, and still equip each office with light from that unit via fiber optic cables. Prior to introduction of restorative materials containing the

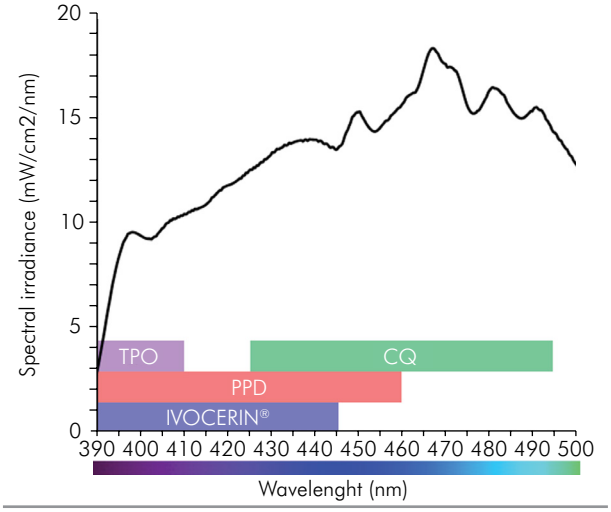

Figure 19. Spectral emission profile of a typical PAC light with absorption wavelength ranges for typical photoinitiators.

alternative photoinitiators, consideration of lasers as the main light-curing source was feasible. A typical argon-ion laser of that time is seen in the Figure 20 and a typical spectral emission profile from an argon-ion laser is seen in the Figure 21.

From the Figure 21, it can be seen that the argon laser emitted longer wavelength power not needed by CQ; however, photons within the CQ range were supplied, so this light functioned well with that photoinitiator. Unfortunately, it can be seen that no light was supplied to activate TPO, and only a small spectral portion of PPD was potentially excited. Thus, once use of the alternative photoinitiators became popular, interest in the argon-ion laser for dental photocuring use rapidly decreased. At this time, Ivocerin® was not commercially available.

Light-emitting diodes

a. Background

Once again, the technology for use of LEDs in dentistry was borrowed from that of other industries already successfully incorporated that concept. LEDs have existed for quite some time, and successful use was made of the red and green-doped compounds. However, inexpensive, high output blue LEDs were a great challenge to make. This particular color was highly researched, because its attainment would lead to the ability to create large screen video displays, emitting the characteristic "RGB" light pattern: red, green, and blue. It was not until the 1990s that blue LEDs became available using indium-gallium-nitride (InGaN) substrates,[21,25] and shortly thereafter, researchers were incorporating them into model dental curing lights. These prototype models proved the concept that the spectral emission from such units could successfully photo-activate CQ-based products. The technology underlying use of these light-emitting devices is solid state: requiring low power, no filament, no optical filter and providing much greater photon-generating efficiency than any competitive light source. In addition, these units can be easily battery powered and the LED sources are claimed to last for thousands of hours, never needing replacement. In a typical circuit, electrons are forced to traverse from one side of a semiconductor material (the "N" material, having an excess of electrons) to a substrate having an electron deficiency (the "P" material). When electrons travel through this potential energy "gap," they also emit light, the specific wavelength of which is determined by the composition of each semiconductor substrate.

b. First generation

The first blue LED curing lights were experimental, prototype models, built to test the concept that they could generate light at the correct wavelength and deliver sufficient number of photons, needed to successfully photocure dental resin-based materials.[25] However, the individual LED elements (5-mm "cans") available at that time, each had a very low output power. This lower power necessitated that

Figure 20. Argon-ion dental light-curing laser.

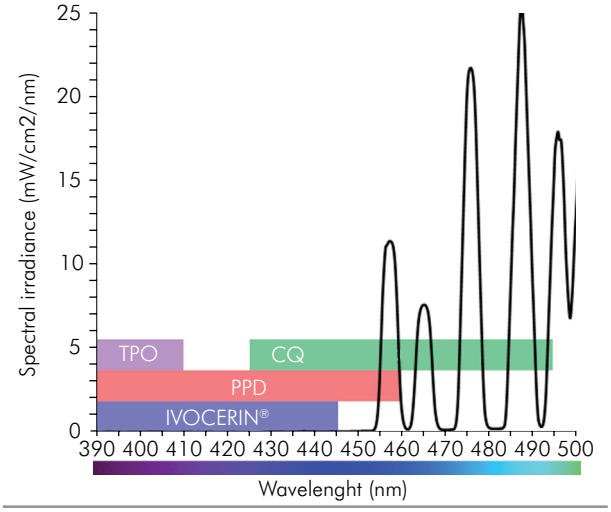

Figure 21. Spectral emission profile of an argon-ion laser curing light with absorption wavelength ranges for typical dental photoinitiators.

the individual LED elements be arranged into a physical array (typically from 8 to 64 in number),[26] and the totality of the output, coupled with use of a irradiance-increasing turbo-tip, provided sufficient output to compete with QTH photocuring of CQ-based composites. An image of a turbo-tip fiber optic light guide is seen in the Figure 22, where the proximal (light-receiving end) has a greater diameter than does the distal (light emitting) end. Arrangement of close-spaced LED cans in a first generation dental, blue LED curing light are seen in the Figure 23.

A means of heat dissipation became needed, because these close-packed arrays generated significant thermal energy within the assembly. Most all units incorporated some sort of heat-sinking technology to draw heat away from the LED chips, so they would not be damaged.

Figure 22. Example of a turbo-tip light guide used to increase irradiance values from lower-powered curing lights.

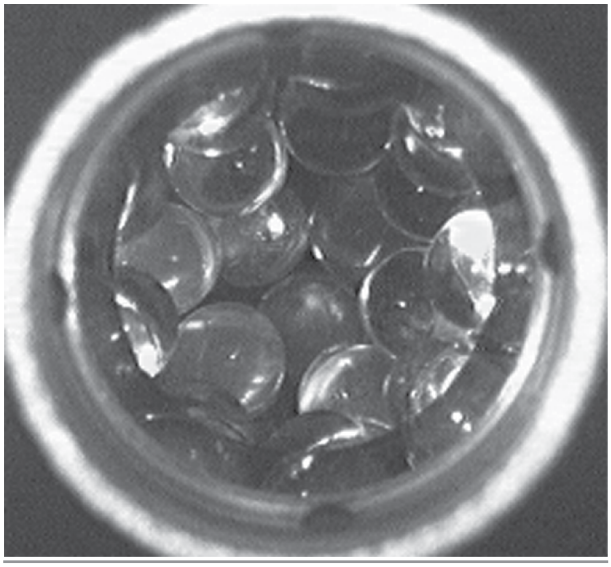

Figure 23. Individual LED can-type emitters closely packed into an array of a first-generation dental LED curing light.

Some pencil-shaped, curing light models used metal body casings that not only provided structural durability, but also provided a large area for thermal dissipation. Later, advancement in LED technology provided the ability to produce flat, very intense, discrete LED chips of small area, but emitting a very intense light. However, the chips were still individual, and were arranged to optimize light output and maximize heat dissipation. An example of such a diode array, along with its large heat sink, are seen Figure 24.

These first generation devices produced relatively low output, but if used for extended exposures, did provide composite curing of CQ-based products that was comparable with the QTH source of that time. Irradiance values of this generation vary greatly, as advancements in LED technology became incorporated into newer products. Battery technology during this time was limited to use of nickel cadmium (NiCAD). Unfortunately, these batteries suffered from what has been called the "memory effect," and careful recharging routines had to be followed, or the useful lifetime of these power sources were significantly reduced.[20] The spectral emission of a light typifying this era is seen in the Figure 25. As can be seen, the spectral emission from this light would be effective toward CQ and PPD, but not for TPO. Ivocerin® was still not available at this time.

Figure 24. Small footprint area chips used in later versions of 1st generation, blue dental light curing units.

c. Second generation

What sparked the great leap in dental LED output was the availability of small footprint, high emission area LEDs that had been developed for the illumination industry.[27] One-Watt chips were now available, all on one body, consisting of 4 main areas of illumination, each consisting of 4, bar-shaped emitting surfaces: a total of 16 emission areas. Incorporation of these chip types, and the higher-power ones to become available shortly thereafter (the 5-Watt devices), greatly boosted irradiant output, and truly allowed blue LEDs to be able to accomplish effective photocuring in a much shorter time.[20] This feat was accomplished by the much greater photon density emitted by these chips within the region that CQ absorbed the highest (460 to 480 nm), compared to that of QTH lights, or even the PAC units. The Figure 26 shows the appearance of these chip arrays in the powered-off and powered-on modes.

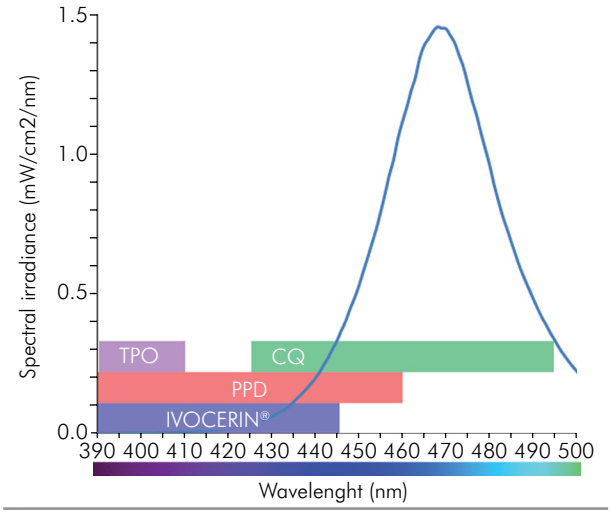

Figure 25. Spectral emission profile of an early, 1st generation blue LED dental curing light.

With advances in chip technology, LEDs consuming 10 and 15 Watts become incorporated, further increasing irradiance values, and allowing lower exposure values, to achieve optimal photocuring of CQ-containing restorative materials.[20,28] During this time, battery technology also advanced, allowing incorporation of the longer-lasting nickel metal hydride (NiMH) units that had no 'memory effect'. However, with the increasing need to dissipate thermal power from the higher-rated LED chips, advanced methods such as internal fans and large metal heat sinks were used to remove the heat from the LED arrays.[20] The spectral emission of a typical second-generation, blue LED curing light is seen in the Figure 27.

Although much greater emission is seen compared to the first generation lights, notice that, with this particular light unit, the peak emission is located at a shorter wavelength than previously seen. Thus, more overlap with PPD is seen, while still providing activation of CQ. Again, no interaction with TPO was possible, and Ivocerin® was still not available during this early time period.

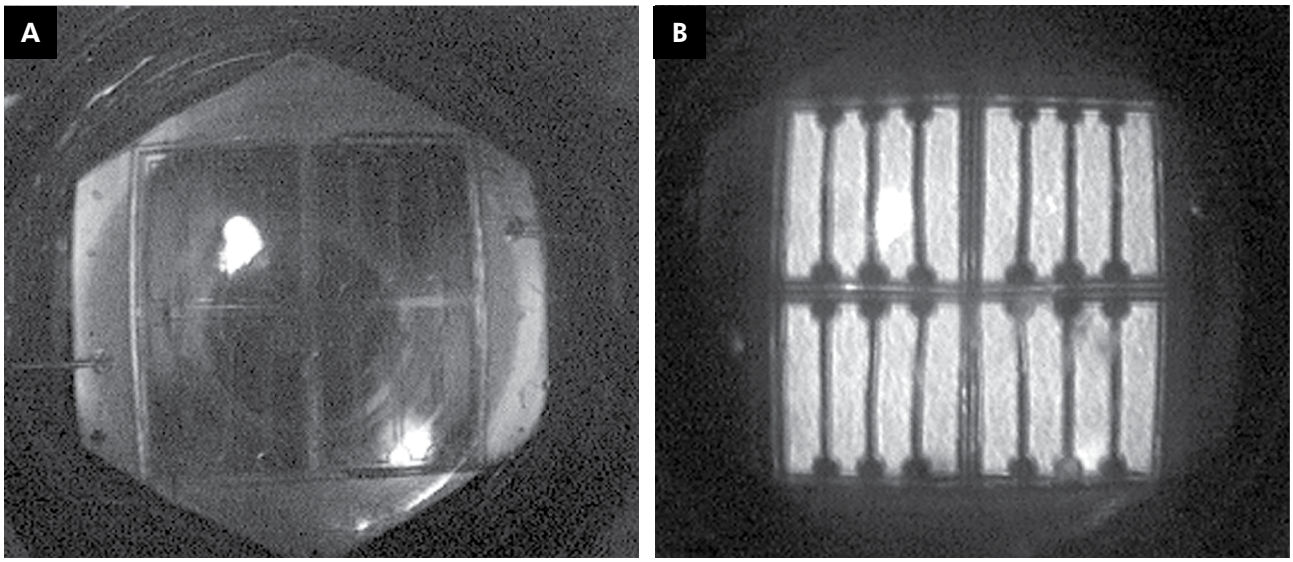

Figure 26. Second generation blue LED chip array, shown in the powered-off (A) and powered-on (B) modes.

d. Third generation

With the increased use of alternative photoinitiators to produce restorations of higher color value, as well as to provide highly reactive initiators to help increase depth of cure, especially for some bulk-cure products, the need to provide radiant energy to activate TPO as well as Ivocerin®, drove manufacturers to incorporate more than one color into the LED chipset. Different schemas were used to provide this simultaneous combination of violet and blue wavelengths. One solution utilized a strong, centrally positioned, high-wattage blue LED, surrounded by 4 lower-powered, converging violet LEDs. This arrangement is seen in the Figure 28.

A different method of incorporating multiple chips into an array is seen in the Bluephase Style light, where two blue LEDs and one violet LED are arranged in an array within the curing light (Figure 29). In this image, the upper-most chip emits violet light, while the two lower chops emit blue. Another method of providing simultaneous blue and violet emission is seen when eliminating one of the 4 blue-emitting pads, and replacing it with a violet emitting LED, as seen in the Figure 30.

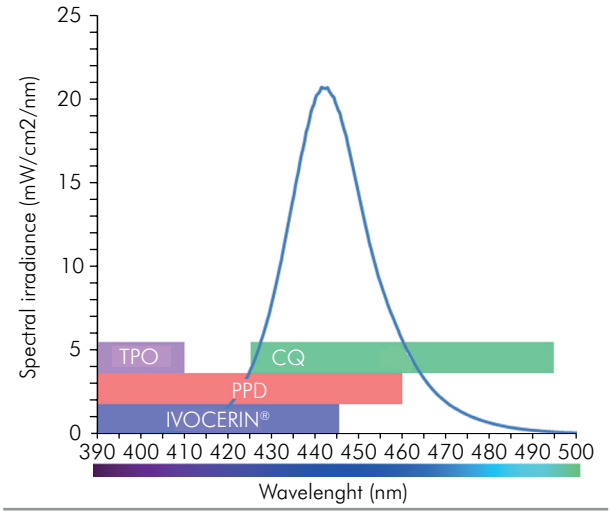

Figure 27. Spectral emission from a typical second generation, blue LED curing light.

Figure 28. Image of the construction of the emitting elements in Ultradent's Ultralume 5 curing light.

Figure 29. Image of the construction of the emitting elements in Ivoclar's Bluephase STYLE curing light.

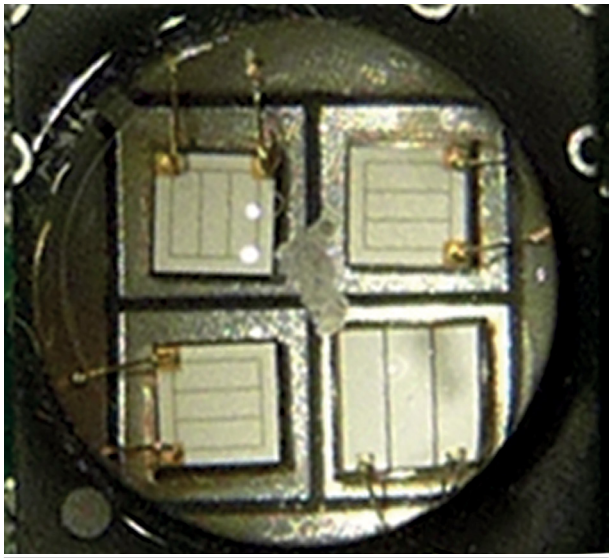

Figure 30. Image of the construction of the emitting elements of a 4 element combination LED array: only the lower left chip emits violet light – the others emit blue light.

One manufacturer has incorporated three different color chips into the single array set: two blue (emitting near 460 nm), a shorter wavelength blue (emitting near 445 nm), and one violet, emitting close to 400 nm). An example of this strategy is seen in the Figure 31. The chips in the upper left and lower right emit blue light near 460 nm, the chip on the upper right emits shorter wavelength light near 445 nm, and the lower left chip emits violet light (near 400 nm). Using these different emitting chipsets, the spectral emission profile of this VALO light is seen in the Figure 32. Note the emission near 400 nm to provide violet, a shorter blue emission near 445 nm, and a stronger blue emission at longer wavelength (460 nm). The totality of these emissions is seen to provide a very wide bandwidth for all possible, contemporary photoinitiators: particularly for TPO, PPD, and CQ. The spectral emission profile of a typical 3rd generation dental LED curing light is seen in the Figure 33.

Notice that, with inclusion of the violet emission near 407 nm, photons are delivered to every possible type of photoinitiator present in any type of product the curing light might be required to activate. However, this ability comes at a price because the blue emission is reduced compared to that of an all-blue emitting light, which means less potential for CQ activation at composite depths. However, in materials that use Lucirin TPO or Ivocerin® in addition to CQ, improved curing is possible, even with lower blue light present.

The third generation curing lights have also seen development of two definite form factors. One factor still utilized a traditional gun style light, with the chip set inside of the gun body, and uses fiber optic light guides to transmit emitted photons onto the target area. Another concept is use of a pencil-style body. This type design can still use removable fiber optic guides, or, instead, can have the emitting chipset placed directly at the distal tip end of the unit, and directed normal to the axis of the unit body. This shines the light directly onto the target, without use of fiber optic light guides. This latter type product has the advantage of greater ease of placement intraorally, which facilitates tip position and allows more direct illumination and maximum transfer of light to the restoration. Different form factor styles of various LED types are seen in the Figure 34. In this figure, note that the top-most light is the pencil style, containing the LED chipset at the distal body end, and directed perpendicular to the long axis of the body. The light below has the LED chips within the distal end of the unit cone, directing their light output parallel to the long axis of the unit body, toward the proximal end of a fiber optic light guide, which is only moderate in length after the guide curvature. The bottom image is a typical "gun" style light, containing the LED chip array in the nosecone of the gun, directing its light toward the proximal end of a fiber optic light guide, quite long in length, after the tip curve.

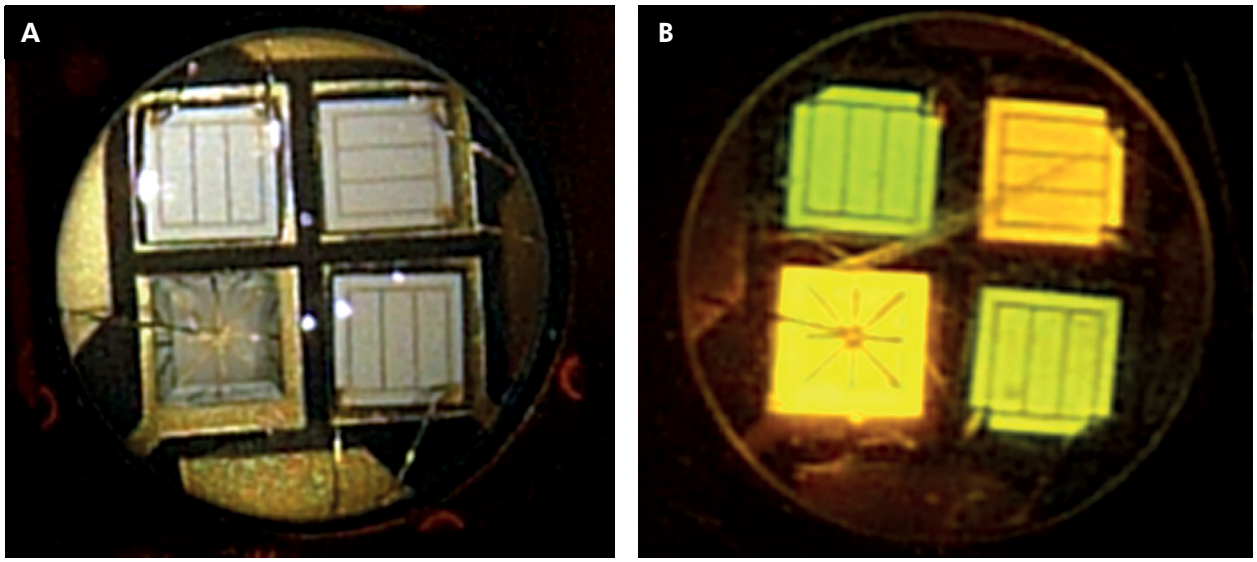

Figure 31. Image of the construction of the emitting elements in Ultradent's VALO curing light: (a) chips off (B) chips on.

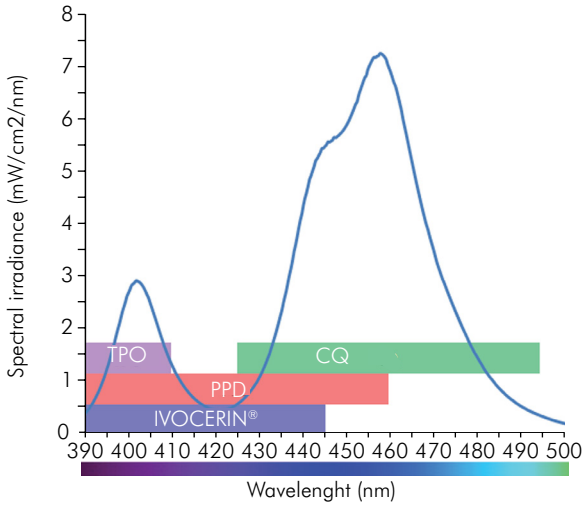

Figure 32. Spectral emission profile of the VALO curing light.

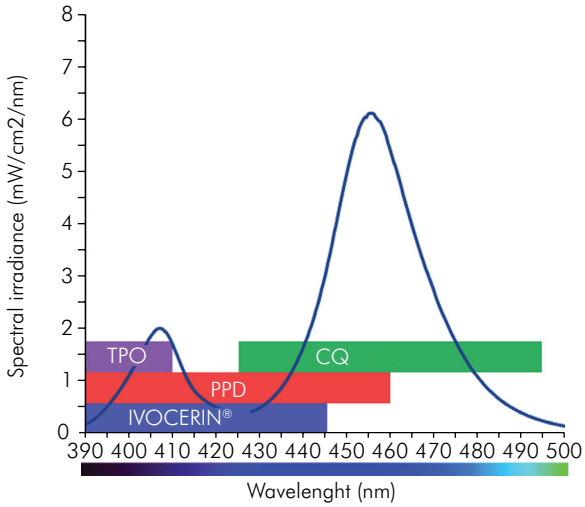

Figure 33. Spectral emission profile of a typical 3rd generation dental LED curing light.

Concurrent with the development of this technology were advancements in battery technology: Most contemporary curing lights now use lithium-ion batteries. These stable, durable, long-usage energy storage sources provide a reliable output over extended clinical operation time.

Contemporary advances – room for improvement

With LED technology now producing very high intensity chip sets, some manufacturers are marketing LED curing lights to clinicians directly over the internet, claiming extraordinarily short exposure durations, and at remarkably low process. However, many of these curing lights have never undergone any testing by regulatory organizations and research shows that many of these units have very poor beam uniformity, provide extremely small optical footprints on the target, and have serious issues with maintaining light output levels through exposures, as a result of poor electronic design, not compensating for battery drain during use.[29] Thus, clinicians should use caution in selecting an untested curing light, because, literally, the clinical success of photo-cured restorations they place depends on the quality of the light source used, as well as the technique the clinician follows.[30]

Figure 34. A variety of form factors of LED curing lights.

Other, very important, clinically relevant issues related to light unit construction and output are focused on the uniformity of irradiance within the projected beam onto the target surface, as well as the pattern of photon wavelengths delivered to restoration areas. If these parameters are not homogeneous, this can contribute to localized under-curing of the resin composite not only at the top, irradiated surface, but also deep within the restoration.[31,32,33]

Enhancement in electrical supply to dental LEDs has also made great strides recently. Development of lithium polymer battery technology has provided for lighter, and more durable power supplies. However, introduction of a totally battery-less dental light-curing unit, that operates by charging and discharging of an "ultra-capacitor" has greatly expanded the lifetime of dental curing lights. Although existing in other

industrial fields, Kerr Dental was the first company to commercially produce such a curing light: The Demi Ultra. This unit claims a full recharge in under 40 seconds, after which, it is said to be capable of providing 25, ten-second exposures, before needing a recharge.[34]

In an attempt to provide very wide light coverage of the target area, Ultradent recently introduced the VALO® Grand LED.[35] This unit is similar to the previous version, except that the emitting area of the lens-covered chip array provides coverage of a 12-mm diameter target area (107 mm^2), whereas, the previous version of this light covered only 78 mm^2, which was still greater than a conventional 8-mm diameter tip that covered only 50 mm^2. This increased area coverage was accomplished, without diminishment of irradiance, as is usually seen when such large diameter beams are utilized, because the manufacture has increased the power output from this light.

Lastly, manufacturers have produced curing lights designed to minimize beam divergence as well as to optimize beam homogeneity, to provide greater irradiance at increased tip-to-target distances. Examples of such units include the SmartLite® Focus, by Dentsply Caulk, Milford, DE, USA),[36] and the Elipar™ DeepCure-S, 3M ESPE, St, Paul, MN, USA).[37]

Effect of light tip to resin distance

Although much of today's dentistry depends on adequate resin photopolymerization, it appears that many dentists take light curing for granted.[38,39] To date, every study published that has evaluated light curing units (LCU) used in dental offices has shown that many are delivering an inadequate light output and are also poorly maintained.[40,41,42,43,44,45,46,47]

In addition to being an averaged value that has been calculated from the power output divided by the tip area, the irradiance values stated by the manufacturers are usually measured only at the light tip. These values can give the dentist the impression they are using a "powerful" curing light, but significantly lower irradiance may be reaching the surface of the resin that is often at least 2 to 8 mm away from the light tip. Thus the irradiance received by the restoration can be very different than at the tip of the light[48] and some curing lights deliver only 25% or less of the irradiance measured at the tip at a distance of just 8 mm away from the tip.[49-53] Consequently, the dentist should know how clinically relevant distances will affect the irradiance delivered by their curing light to the restoration (Figure 35).

This information is highly relevant at the gingival margin region that is at high-risk for recurrent caries.[54] This region is the most difficult to reach with the curing light and is furthest away from the light source.[50,55] Consequently, the resin here will receive the least amount of light and may well be undercured.[49,50,51,52,53,56] This may result in reduced bond strengths at this critical part of the restoration. Xu et al. investigated the adhesion of composite resin as the distance from the light guide increased.[52] Their conclusion was that when curing adhesives in deep proximal boxes with a curing light of 600 mW/cm^2, the curing time should be increased to 40 to 60 seconds to ensure optimal polymerization. Others have also made similar recommendations to increase the curing time, even for curing lights that deliver more than 1,000 mW/cm^2.

Light beam uniformity

Several publications have shown that light emitted from many LED-curing lights is not evenly distributed across the light tip. Laser beam analyzers have been used to measure where the light is emitted from the

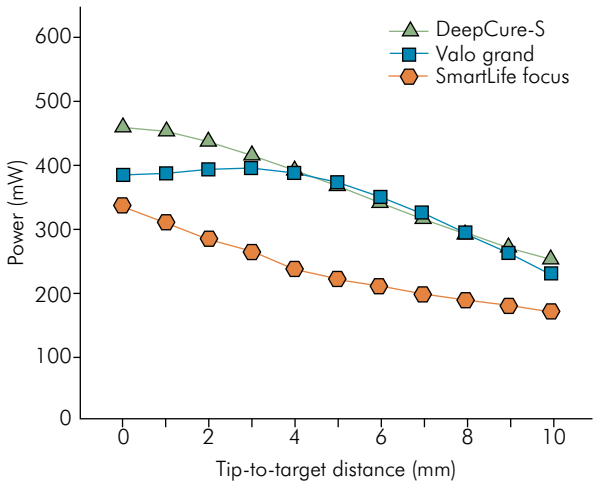

Figure 35. Power (mW) versus tip-to-target distance (mm) graph showing how the distances affect the irradiance delivered by three curing lights.

curing light.[31,32,33,49,53,57,58] These cameras take a digital image of the light output and the power received by each pixel in the camera sensor is reported. Figure 36 illustrates two curing lights, one with a uniform light output and one with a "hot spots" of very bright light and "cold spots" where very little light comes from the light tip.

Scaled images of the beam profile can be superimposed over a tooth preparation to demonstrate the regions of the preparation that are not receiving adequate radiant exposure to cure a dental resin. Figure 37 illustrates how some lights may not cover the entire restoration and the proximal boxes may receive and inadequate amount of light, especially the entire restoration receives just one light exposure.[31,33,38,39] For other lights, the irradiance is uniformly delivered over the entire surface of wide light tips that can completely cover the restoration. Such information is invaluable to the dentist when deciding which curing light to purchase.

The "blue light hazard"

We have known for many years that cumulative exposures to high intensity blue light may cause ocular damage.[59-61] This Blue Light Hazard to the retina is greatest at 440 nm,[62] which is close to the maximum emission from dental LCUs (Figures 38A and 38B).[20,39] Blue light is transmitted through the ocular media and absorbed by the retina. While high levels of blue light cause immediate and irreversible retinal burning, chronic exposure to low levels of blue light is thought to cause accelerated retinal aging and degeneration and can accelerate age-related macular degeneration (ARMD).[63,64]

Most countries follow international guidelines on optical radiation, such as those from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and American Conference of Governmental Industrial Hygienists (ACGIH).[62,63] A recent study found that these ACGIH limits may be easily reached during a normal workday by dental personnel using high power curing lights[59] unless the operator wears orange protective glasses. If they do not wear these orange 'blue blockers' and they look at the light for the first second of the curing cycle before averting their eyes, it may take as little as seven curing cycles to exceed the maximum daily cumulative exposure.[59] It should also be noted that the maximum recommended exposure times are for individuals with normal photosensitivity and patients or dental personnel who have had cataract surgery, or who are taking photosensitizing medications, have a greater susceptibility for retinal damage and

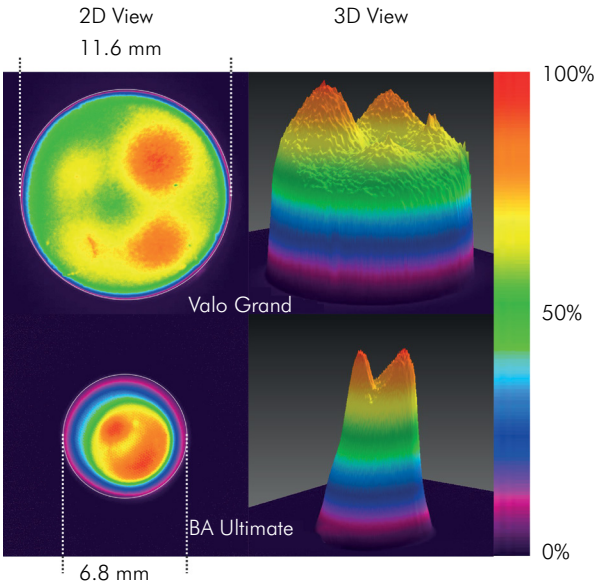

Figure 36. Light beam uniformity from two curing lights, one with a uniform light output (top figures) and one with a "hot spots" of very bright light and "cold spots" (bottom figures).

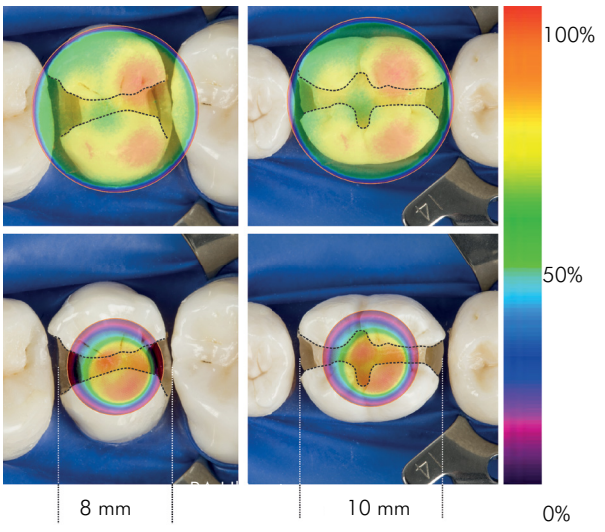

Figure 37. Clinical scenarios showing that some lights may not cover the entire restoration.

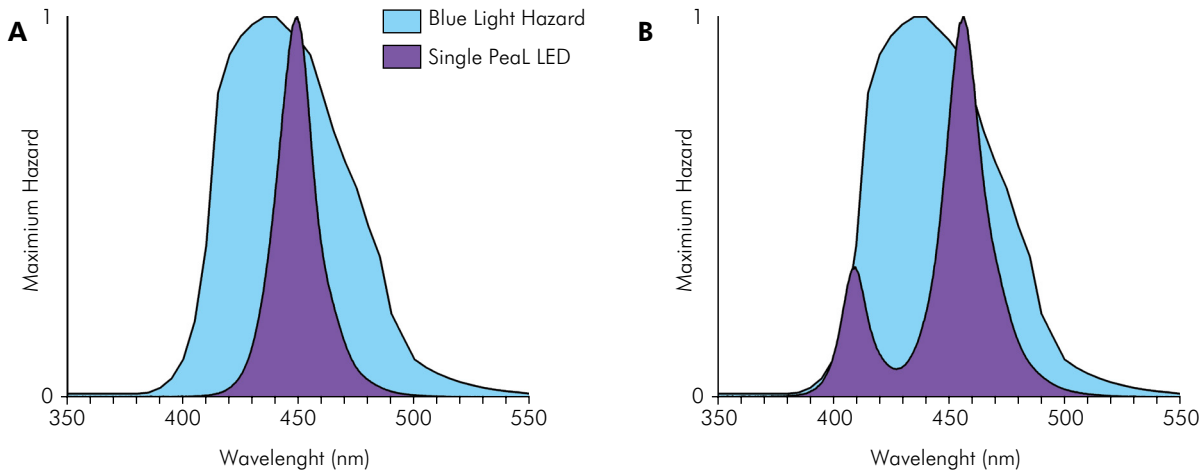

Figure 38. Maximum hazard versus wavelength (nm) graph for single peak (A) and broadband LED light-curing units.

ocular injury may occur with even shorter exposure times.[62,63] As dental professionals we must be aware and use proper protection from the 'blue light' hazard. Blue light filtering glasses ('orange blue-blockers') can reduce the transmission of light below 500 nm to less than 1%.[32,39] When such blue light filtering glasses are used, the operator can safely watch what they are doing when light curing. This will improve the amount of light delivered to the restoration.[65-67]

Monitoring

For optimal operation of a curing light, it is important that there is a routine evaluation of the curing light's status (Figure 39). However, it is impossible for the clinician to evaluate the quantity and quality of the light being discharged to polymerize a restoration just by looking at the light. The brightness of the blue light and the hard resin surface can provide a false sense of security that the light is adequately polymerizing the restorative material. As the curing light gets older, there can be a decrease in the light output due to degradation of the light source,[68] autoclaving the fiber-optic light probe,[69] breakage and fracture of the light tip,[70] and/or the presence of cured composite resin or debris on the exposed light tip.[70,71] Thus the clinician should record the light output from their curing light when new and then routinely monitor its light output using the same conditions (light guide, barrier, setting) and the same dental radiometer. When the light output starts to decline, initially they can compensate for this fall by increasing the exposure time, but later, they should purchase a new curing light.

Infection control

It is recommended to use infection control barriers over curing lights and light guides. Unfortunately, the preformed barriers that slip over a light guide are not standardized to optimize light transmission. Research has shown that some barriers can reduce irradiance from a curing light up to 40% and it is important not to place the seam of the protective sleeve over the light tip because this will further reduce the light output.[57,72,73] When using cold sterilizing techniques to clean a curing light, approved cleaning solutions should be used. The light guide should be removed from time to time and the lens or filter inside the curing light housing checked to ensure it is clean, as are both ends of the light guide.

Effect of training

Currently only minimal training is provided to dentists, dental students and dental assistants how to use a curing light. While there are elaborate descriptions of multistep techniques for material manipulation and placement, at a most critical phase of the technique, usually there are only five words - "and then you light cure".[74] It has been shown that it is not as simple as aiming the curing light

Figure 39. Evaluation of the curing light's status with radiometer.

at the tooth, turning it on and then not watching what you are doing while light curing.[65,75,76] When the curing light is used correctly, the dentist can significantly improve the amount of light they deliver to the restoration.

Light attenuation by absorbing characteristics of indirect restorative materials

The light absorption of indirect restorative materials depends on their composition, thickness, shade and opacity. The indirect materials commonly used are composite resins, glass and polycrystalline (or zirconia) ceramics, which present different optical and light absorption properties that influence light attenuation during light-activation of an underlying resin cement.[77-80] To overcome the effects of curing light attenuation, dual-cured cementing systems were developed and some of them are used in combination with adhesive systems, which contain co-initiators, such as sulfinic acid salts that produce free radicals and contribute to the polymerization reaction of the dual-cured resin cements.[81-82] However, when light activated the most of cementing systems generate higher degree of conversion values than autopolymerizing mode, which can compromise some properties of resin cement, such as flexural strength, modulus, hardness, solubility and water sorption.[83-86] Thus, the self-curing reaction seem not be sufficiently efficient to ensure high monomeric conversion levels in the absence of light.

An evaluation of visible light power density measured through glass slide and through 2-mm thick A2 and A4-shade procured resin discs showed that the when the A2-shade pre-cured resin disc was used, irradiance decreased approximately 89%, while 92% lower irradiance was noted when using the A4 disc.[87] The authors concluded that the presence of an indirect restoration can decrease the degree of conversion of some dual-cured cementing systems because the light attenuation caused by resin discs. Another study analyzed the effect of types (resin hybrid and feldspathic ceramic) and thicknesses (0.5, 1.0, 1.5 and 2.0 mm) of millable restorative materials with similar shades (A2 and 2M2C, respectively) on degree of conversion of one commercial dual-cured, self-adhesive resin cement. This study did not find significant differences between materials when using the same thickness and reported that the light attenuation caused by 2.0-mm thick millable materials for CAD-CAM system resulted in significantly lower degree of conversion than those obtained with thin materials (0.5 and 1.0 mm thick), which did not differ from the direct light exposure of resin cement (without material interposition).[80]

Effects of curing light on the temperature of tooth pulp and soft tissues

The heat generated during restorative procedures has always been a matter of concern among clinicians and researchers.[88,89,90] Over decades, several studies have investigated the heat on the *in vitro* temperature within the pulp chamber caused by cavity preparation with slow and high speed handpieces,[91,92] by restorative materials with exothermic setting, restoration finishing and polishing, as well as by the light emitted from light curing.[93,94,95,96,97,98,99,100] Recently, because new LED light-curing units with radiant exitance values exceeding 2,000 mW/cm^2 have become commercially available,[20-101] the heat generated from these devices has become an important clinical issue.

Effects of heat on pulp temperature

Dental pulp is a highly vascularized tissue and contains the main regulatory system for heat distribution in teeth, capable of dissipating the heat transferred by external thermal stimuli to the dentin/pulp complex.[102,103] Conversely, it consists of a relatively large amount of tissue encased in hard dentinal walls and has a terminal circulation with no collateral blood supply.[104] For this reason, dental pulp is vulnerable to a rise in temperature when exposed to a thermal stimulus.[105]

The effects of heat on pulp have been well documented in the literature. Based on microscopic observations on living dental pulp, Pohto and Scheinin concluded that therapeutic procedures in dentistry may easily cause a rise in tooth temperature to a degree that irreversible changes in the pulp may occur.[106] The *in vivo* effects of heat on pulp temperature and its biological consequences were also demonstrated by Zach and Cohen in 1965.[89] In that study, a 5.5°C pulp temperature rise in *rhesus* monkeys, from application of a hot metal source to the facial enamel surface, induced necrosis in 15 % of evaluated pulps. Although Brännström *et al*. advised that almost any heat is able to cause pulpal necrosis in old pulp,[107] all *in vitro* and *in vivo* studies addressing the effects of LCU light on pulp temperature assumed the 5.5°C rise as the threshold temperature to determine whether their findings may be harmful for the pulp after Zach and Cohen's findings were published.

Temperature rise within the pulp chamber caused by the light curing unit (LCU)

The first *in vitro* analyses evaluated the temperature rise within the pulp chamber when extracted teeth were exposed to light emitted from QTH, Plasma Arc, and first generation LED units.[98,108,109,100,11,112] Overall, the use of QTH and Plasma Arc lights caused higher temperature rise within the pulp chamber in comparison to the first generation LED evaluated in those studies.[98,108,109,110] At that time, such differences in the temperature rise were attributed to the differences in the curing light outputs, because compared to the QTH light, no light was emitted by the LED curing lights in the infrared range.[108] It should be mentioned however, that the first generation LED units emitted light at a considerably lower irradiance (approximately 240 mW/cm^2) level than did QTH lights (approximately 450–1200 mW/cm^2).[56,96,110,113]

With the advances in LED technology, the second and third generation of LED units were developed.[20,113] These new devices have a considerably greater light output compared to earlier versions.[20,27,113] As a consequence, the heat generated by the light emitted from such LED units was comparable to or even higher than the heat generated from QTH lights.[96,97,114,115] In addition, the third generation LED units have blue and violet LED chips, so they emit light with more than one wavelength.[20,32,56] Despite the difference in the light outputs among QTH, second, and third generations LED curing lights, and in contrast to previous assumptions, the differences in the temperature rise within the pulp chamber have been attributed to higher radiant exitance along with exposure period than to the light beam profile itself.[116,117]

Although the heat released during the exothermic reaction of composite resins may contribute to pulp temperature rise,[93,97,99] curing lights remain the most responsible heat source for the temperature rise within the pulp.[93,99] Therefore, the curing light type, radiant exitance, radiant exposure values, and light beam profile play an important role in pulp temperature rise.[99,101,114,115,118,119,120] In this regard, curing lights emitting light with higher radiant exitance for longer exposure periods generate more heat than lights with lower radiant exitance values.[96,110,120] In addition, LCU design has been shown to influence the pulp temperature rise during light exposure. For instance, LED units with pulse output technology such as LEDemetron II[121] help reducing pulp temperature rise.[122] In the other hand, LED units with diodes placed on the light tip may cause a higher pulp temperature rise.[122]

Despite the attempts to develop reliable and predictable methodologies to reproduce the *in vivo* condition, a wide range from 1.5 to 23.2 °C in the *in vitro* pulp temperature rise during exposure to light emitted by such LCUs has been reported.[97,100,101,103,114,123,124,125] Such a discrepancy among results might be related to the variety of LCU types, brands, and irradiances evaluated in those studies,[97,100,101,103,114,123,124,125] differences in tooth

type and anatomy,[97,100,101,123] the presence of cavities either with or without restorative procedures,[97,114,116] as well as the thickness of remaining pulpal wall.[123,126] Although such differences between methods do not allow any reliable comparison among studies in order to establish a critical parameter for the use of LCUs to reduce the risk of pulpal damage, several *in vitro* studies concluded that light emitted from high power LCUs can be harmful for the pulp depending on the radiant exitance and exposure period.[101,120] Indeed, based on *in vitro* results, some authors suggested that the use of LCUs with higher irradiance values than 1,200 mW/cm^2 may harm the pulp tissue.[117] Similarly, other authors advised that clinicians should limit the exposure time to 20 s when the irradiance from LED units ranges from 1,200 to 1,600 mW/cm^2, while exposure period should not be longer than 10 s when the LCU irradiance ranges from 2,000 to 3,000 mW/cm^2.[101] However, most authors agreed that *in vitro* simulation does not reproduce the complexities of an *in vivo* scenario, which includes the presence of pulp tissue and the dynamic blood flow mechanisms to control pulp temperature.[93,97,100,120,127] Therefore, care should be taken when interpreting *in vitro* results.

Recently, an *in vivo* study evaluated the pulp temperature rise in intact human premolars.[120] In that study, the probe of a temperature acquisition system was inserted within the pulp of anesthetized upper premolars and significant rise in pulp temperature was observed when the buccal surface was exposed to light emitted from a *polywave*® LED unit at varying radiant exposure values. A linear relationship between radiant exposure values (J/cm^2) and pulp temperature rise was established, so the previous *in vitro* findings that higher irradiance together with longer exposure periods are responsible for higher pulpal temperature rise were confirmed *in vivo*. However, in contrast to previous *in vitro* results,[19] longer exposure periods (60 seconds) were required *in vivo* to cause a pulp temperature rise to values higher than 5.5°C when light with radiant exitance values of approximately 1,200 mW/cm^2 were delivered to intact premolars.[120] The pulp temperature values recorded *in vivo* were also lower than the *in vitro* ones from studies simulating pulp flow at varying flow rates, which are known to act as heat sink.[100,103] Therefore, the lower pulpal temperature rise observed *in vivo* confirms that the dynamic changes in the pulp when temperature changes in this tissue occur[128] are crucial when regulating pulp temperature *in vivo*. In other words, when blue light strikes the enamel surface, part of the light energy is reflected, part is converted into thermal energy, while the remaining portion passes through to the substrates below.[129] When blue light reaches the pulp tissue, photons are strongly absorbed by the blood chromophores to be partly converted into thermal energy,[130] resulting in a slower pulp temperature increase *in vivo* than that observed *in vitro*. Because of the constant blood flow, the warmed chromophores from absorbed photons are quickly replaced by other, cooler ones, so most of the heat generated in this tissue is dissipated. However, it should be emphasized that all analyses in that *in vivo* study were performed on intact premolars. In that clinical condition, a 3-mm thick barrier composed of enamel and dentin is capable of absorbing and storing heat to protect the pulp against thermal injury.[131,132] Therefore, a greater pulp temperature rise is expected with shorter exposure periods on teeth having deep cavities having a thin pulpal floor.

Temperature increase on soft tissues

To date, little information regarding the effects of LCU light on temperature of soft tissues such as gingiva is available in the literature, although some studies have raised concerns about the potential harm the light emitted by these LCUs can cause on soft tissues.[56,117] The only report addressing this issue on human soft tissues to date described three clinical cases in which the patients showed lesions on the lower lip in a location that would have been apical to the placed restoration while the rubber dam was in position.[133] Recently, an *in vivo* study performed on swine gingiva evaluated the temperature increase on the gingival tissue during the exposure to light emitted from a high-power polywave® LCU.[134] In that study, exposure to light with radiant exitance values of approximately 1,200 mW/cm^2, increased the gingival temperature to approximately 41°C. Although the temperature increase that cause severe thermal damage on the gingival tissue is still unknown, approximately 67 % and 77 % of

the tissues exposed to light for 40 and 60 seconds, respectively, developed a gingival lesion. In addition, according to the authors, the use of rubber dam neither prevented the temperature rise nor the development of gingival lesions.

Methods to reduce the temperature rise on the pulp and soft tissues

Despite all concern regarding the pulp temperature rise during exposure to LCU light, little attempt has been made to establish alternative approaches to avoid excessive rises in pulp temperature during restorative procedures that use LCUs.[122] To the extent of our knowledge, the only study that evaluated the effects of alternative approaches to reduce pulp temperature rise during exposure to LCU light found that air flow, water, or air/water spray applied during the exposure to LCU light were capable of reducing the pulp temperature rise in extracted molars restored with indirect ceramic restoration.[122] However, the use of water or air/water spray during the exposure of resin composite layers to light on direct restorative procedures should be avoided as water may impair the bonding between the adhesive layer and resin composite, as well as the resin.[135] Therefore, although further *in vitro* and *in vivo* studies are still required, the directing a stream of air towards the tooth during the exposure to light seems promising.

Some clinicians may believe that other methods, such as increasing the distance between the LCU tip and the tooth, or reducing the irradiance, can help protect the pulp against thermal injury. However, because the drop in the radiant exitance values with increasing distance between the LCU tip and the tooth may vary among LCUs, such procedures may compromise optimal polymerization of the resin composite in the most difficult regions for the light to reach in the cavity, such as cervical regions of Class II cavity preparations.[50,56]

With regard to the protection of soft tissues, once the use of rubber dam does not protect the gingival tissue against heat, some authors have advised clinicians to place gauze under the rubber dam.[117,133] In addition, care should be taken to ensure that no soft tissue is directly exposed to light from the LCU tip, even if the tissues are covered by a rubber dam.[133]

References

1. Leprince JG, Palin WM, Hadis MA, Devaux J, Leloup G. Progress in dimethacrylate-based dental composite technology and curing efficiency. Dent Mater. 2013;29(2):139-56. https://doi.org/10.1016/j.dental.2012.11.005
2. Rueggeberg FA. From vulcanite to vinyl, a history of resins in restorative dentistry. J Prosthet Dent. 2002;87(4):364-79. https://doi.org/10.1067/mpr.2002.123400
3. Craig R. Symposium on composite resins in dentistry. In: Horn H, editor. The dental clinica of North America. Philadelphia: Saunders; 1981. p. 219-39.
4. Craig RG. Denture materials and acrylic base materials. Curr Opin Dent. 1991;1(2):235-43.
5. Mark A. ADAF Paffenbarger Research Center: where many new ideas for dentistry start. J Am Dent Assoc. 2009;140 Suppl 1:10-1s. https://doi.org/10.14219/jada.archive.2009.0353
6. Peutzfeldt A. Resin composites in dentistry: the monomer systems. Eur J Oral Sci. 1997;105(2):97-116. https://doi.org/10.1111/j.1600-0722.1997.tb00188.x
7. Albers H. Resins and polymerization: tooth-colored restoratives. 8th ed. Santa Rosa, CA: Alto; 1996. p. 5a1-8.
8. Buonocore MG. Retrospections on bonding. Dent Clin North Am. 1981;25(2):241-55.
9. Paffenbarger GC, Rupp NW. Composite restorative materials in dental practice: a review. Int Dent J. 1974;24(1):1-11.
10. Albers H. Resin curing systems. Tooth-colored Restoratives. 8th ed. Santa Rosa, CA: Alto; 1996. p. 5b1-9.
11. Craig RG. Chemistry, composition, and properties of composite resins. Dent Clin North Am. 1981;25(2):219-39.
12. Main C, Cummings A, Moseley H, Stephen KW, Gillespie FC. An assessment of new dental ultraviolet sources and u.v.-polymerized fissure sealants. J Oral Rehabil. 1983;10(3):215-27. https://doi.org/10.1111/j.1365-2842.1983.tb00115.x
13. 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. https://doi.org/10.4012/dmj.2009-137

14. Dart E, Mencek J, Inventors. Imperial Chemical Industries Limited, London, assignee. Photopolymerizable composition. United States patent US 4,071,424;1978.
15. Chen YC, Ferracane JL, Prahl SA. Quantum yield of conversion of the photoinitiator camphorquinone. Dent Mater. 2007;23(6):655-64. https://doi.org/10.1016/j.dental.2006.06.005
16. Oliveira DC, Rocha MG, Correa IC, Correr AB, Ferracane JL, Sinhoreti MA. The effect of combining photoinitiator systems on the color and curing profile of resin-based composites. Dent Mater. 2016 Oct;32(10):1209-17. https://doi.org/10.1016/j.dental.2016.06.010
17. Neumann MG, Schmitt CC, Ferreira GC, Corrêa 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):576-84. https://doi.org/10.1016/j.dental.2005.06.006
18. Neumann MG, Miranda WG Jr, Schmitt CC, Rueggeberg FA, Correa IC. Molar extinction coefficients and the photon absorption efficiency of dental photoinitiators and light curing units. J Dent. 2005 Jul;33(6):525-32. https://doi.org/10.1016/j.jdent.2004.11.013
19. 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):369-75. https://doi.org/10.1016/j.dental.2008.08.003
20. Rueggeberg FA. State-of-the-art: dental photocuring: a review. Dent Mater. 2011;27(1):39-52. https://doi.org/10.1016/j.dental.2010.10.021
21. Rueggeberg F. Contemporary issues in photocuring. Compend Contin Educ Dent. 1999;(25):S4-15.
22. Friedman J, inventor. Dental light curing lamp unit with interchangable autofocus light guides. United States patent US 4,948,215;1990.
23. Curtis JW Jr, Rueggeberg FA, Lee AJ. Curing efficiency of the Turbo Tip. Gen Dent. 1995;43(5):428-33.
24. Yap AU, Soh MS, Siow KS. Post-gel shrinkage with pulse activation and soft-start polymerization. Oper Dent. 2002;27(1):81-7.
25. Mills RW. Blue light emitting diodes: another method of light curing? Br Dent J. 1995;178(5):169. https://doi.org/10.1038/sj.bdj.4808693
26. Kennedy J, Kayser R, Inventors. Portable light emitting diode apparatus with semiconductor emitter array. United States patent US 5,634,711.1997.
27. Rueggeberg FA, Blalock JS, Callan RS. LED curing lights: what's new? Compend Contin Educ Dent. 2005;26(8):586-91.
28. Uhl A, Sigusch BW, Jandt KD. Second generation LEDs for the polymerization of oral biomaterials. Dent Mater. 2004;20(1):80-7. https://doi.org/10.1016/S0109-5641(03)00095-2
29. AlShaafi MM, Harlow JE, Price HL, Rueggeberg FA, Labrie D, AlQahtani MQ et al. Emission characteristics and effect of battery drain in "budget" curing lights. Oper Dent. 2016;41(4):397-408. https://doi.org/10.2341/14-281-L
30. Mutluay MM, Rueggeberg FA, Price RB. Effect of using proper light-curing techniques on energy delivered to a Class 1 restoration. Quintessence Int. 2014;45(7):549-56.
31. Michaud PL, Price RB, Labrie D, Rueggeberg FA, Sullivan B. Localised irradiance distribution found in dental light curing units. J Dent. 2014;42(2):129-39. https://doi.org/10.1016/j.jdent.2013.11.014
32. Price RB, Labrie D, Rueggeberg FA, Felix CM. Irradiance differences in the violet (405 nm) and blue (460 nm) spectral ranges among dental light-curing units. J Esthet Restor Dent. 2010;22(6):363-77. https://doi.org/10.1111/j.1708-8240.2010.00368.x
33. Price RB, Labrie D, Rueggeberg FA, Sullivan B, Kostylev I, Fahey J. Correlation between the beam profile from a curing light and the microhardness of four resins. Dent Mater. 2014;30(12):1345-57. https://doi.org/10.1016/j.dental.2014.10.001
34. The Kerr Corporation. DemiTM Ultra: LED ultracapacitor curing light system. Product brochure. Orange: Kerr; 2013.
35. Ultradent Products. VALO® Grand Product Prochure S. Jordan: Ultradent; 2016 [acess year Month day]. Available from: https://www.ultradent.com/en-us/VALO-Grand-LED-Curing-Light/default.aspx
36. Dentsply Caulk. SmartLite® Focus Product Brochure, Form 544904 (R 3/20/14). Milford: Dentsply Caulk; 2014.
37. 3M Oral Care. Elipar™ DeepCure-S Product Brochure #70-2013-0701-7. St. Paul: 3M Oral Care; 2016.
38. Strassler HE, Price RB. Understanding light curing, Part I. Delivering predictable and successful restorations. Dent Today. 2014;33(5):114-8.
39. Price RB, Ferracane JL, Shortall AC. Light-Curing units: a review of what we need to know. J Dent Res. 2015;94(9):1179-86. https://doi.org/10.1177/0022034515594786
40. Al Shaafi M, Maawadh A, Al Qahtani M. Evaluation of light intensity output of QTH and LED curing devices in various governmental health institutions. Oper Dent. 2011;36(4):356-61. https://doi.org/10.2341/10-247-O
41. Hao X, Luo M, Wu J, Zhu S. A survey of power density of light-curing units used in private dental offices in Changchun City, China. Lasers Med Sci. 2015;30(2):493-7. https://doi.org/10.1007/s10103-013-1351-0
42. Hegde V, Jadhav S, Aher GB. A clinical survey of the output intensity of 200 light curing units in dental offices across Maharashtra. J Conserv Dent. 2009;12(3):105-8. https://doi.org/10.4103/0972-0707.57633
43. Barghi N, Fischer DE, Pham T. Revisiting the intensity output of curing lights in private dental offices. Compend Contin Educ Dent. 2007;28(7):380-4.
44. Miyazaki M, Hattori T, Ichiishi Y, Kondo M, Onose H, Moore BK. Evaluation of curing units used in private dental offices. Oper Dent. 1998;23(2):50-4.

45. Ernst CP, Busemann I, Kern T, Willershausen B. Feldtest zur Lichtemissionsleistung von Polymerisationsgeräten in zahnärztlichen Praxen. Dtsch Zahnarztl Z. 2006;61:466-71.
46. El-Mowafy O, El-Badrawy W, Lewis DW, Shokati B, Soliman O, Kermalli J, et al. Efficacy of halogen photopolymerization units in private dental offices in Toronto. J Can Dent Assoc. 2005;71(8):587.
47. Maghaireh GA, Alzraikat H, Taha NA. Assessing the irradiance delivered from light-curing units in private dental offices in Jordan. J Am Dent Assoc. 2013;144(8):922-7. https://doi.org/10.14219/jada.archive.2013.0210
48. Catelan A, Araújo LS, Silveira BC, Kawano Y, Ambrosano GM, Marchi GM et al. Impact of the distance of light curing on the degree of conversion and microhardness of a composite resin. Acta Odontol Scand. 2015;73(4):298-301. https://doi.org/10.3109/00016357.2014.946965
49. Price RB, Labrie D, Whalen JM, Felix CM. Effect of distance on irradiance and beam homogeneity from 4 light-emitting diode curing units. J Can Dent Assoc. 2011;77:b9.
50. Price RB, Dérand T, Sedarous M, Andreou P, Loney RW. Effect of distance on the power density from two light guides. J Esthet Dent. 2000;12(6):320-7. https://doi.org/10.1111/j.1708-8240.2000.tb00241.x
51. Corciolani G, Vichi A, Davidson CL, Ferrari M. The influence of tip geometry and distance on light-curing efficacy. Oper Dent. 2008;33(3):325-31. https://doi.org/10.2341/07-94
52. Xu X, Sandras DA, Burgess JO. Shear bond strength with increasing light-guide distance from dentin. J Esthet Restor Dent. 2006;18(1):19-27. https://doi.org/10.2310/6130.2006.00007
53. Vandewalle KS, Roberts HW, Andrus JL, Dunn WJ. Effect of light dispersion of LED curing lights on resin composite polymerization. J Esthet Restor Dent. 2005;17(4):244-54. https://doi.org/10.1111/j.1708-8240.2005.tb00122.x
54. Mjör IA. Clinical diagnosis of recurrent caries. J Am Dent Assoc. 2005;136(10):1426-33. https://doi.org/10.14219/jada.archive.2005.0057
55. Yearn JA. Factors affecting cure of visible light activated composites. Int Dent J. 1985;35(3):218-25.
56. Price RB, Shortall AC, Palin WM. Contemporary issues in light curing. Oper Dent. 2014;39(1):4-14. https://doi.org/10.2341/13-067-LIT
57. Vandewalle KS, Roberts HW, Rueggeberg FA. Power distribution across the face of different light guides and its effect on composite surface microhardness. J Esthet Restor Dent. 2008;20(2):108-17. https://doi.org/10.1111/j.1708-8240.2008.00160.x
58. Haenel T, Hausnerová B, Steinhaus J, Price RB, Sullivan B, Moeginger B. Effect of the irradiance distribution from light curing units on the local micro-hardness of the surface of dental resins. Dent Mater. 2015;31(2):93-104. https://doi.org/10.1016/j.dental.2014.11.003
59. Labrie D, Moe J, Price RB, Young ME, Felix CM. Evaluation of ocular hazards from 4 types of curing lights. J Can Dent Assoc. 2011;77:b116.
60. McCusker N, Lee SM, Robinson S, Patel N, Sandy JR, Ireland AJ. Light curing in orthodontics; should we be concerned? Dent Mater. 2013;29(6):e85-90. https://doi.org/10.1016/j.dental.2013.03.023
61. Bruzell Roll EM, Jacobsen N, Hensten-Pettersen A. Health hazards associated with curing light in the dental clinic. Clin Oral Investig. 2004;8(3):113-7. https://doi.org/10.1007/s00784-003-0248-x
62. American Conference of Governmental Industrial Hygienists. TLVs and BEIs based on the documentation for threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati: American Conference of Governmental Industrial Hygienists; 2013.
63. International Commission on Non-Ionizing Radiation Protection. Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38 to 3 microM). Health Phys. 1997;73(3):539-54.
64. Ham WT Jr, Ruffolo JJ Jr, Mueller HA, Clarke AM, Moon ME. Histologic analysis of photochemical lesions produced in rhesus retina by short-wave-length light. Invest Ophthalmol Vis Sci. 1978;17(10):1029-35.
65. Federlin M, Price R. Improving light-curing instruction in dental school. J Dent Educ. 2013;77(6):764-72.
66. Price RB, McLeod ME, Felix CM. Quantifying light energy delivered to a Class I restoration. J Can Dent Assoc. 2010;76:a23.
67. Seth S, Lee CJ, Ayer CD. Effect of instruction on dental students' ability to light-cure a simulated restoration. J Can Dent Assoc. 2012;78:c123.
68. Friedman J. Variability of lamp characteristics in dental curing lights. J Esthet Dent. 1989;1(6):189-90. https://doi.org/10.1111/j.1708-8240.1989.tb00500.x
69. Rueggeberg FA, Caughman WF, Comer RW. The effect of autoclaving on energy transmission through light-curing tips. J Am Dent Assoc. 1996;127(8):1183-7. https://doi.org/10.14219/jada.archive.1996.0409
70. Poulos JG, Styner DL. Curing lights: changes in intensity output with use over time. Gen Dent. 1997;45(1):70-3.
71. Strydom C. Dental curing lights: maintenance of visible light curing units. SADJ. 2002;57(6):227-33.
72. Coutinho M, Trevizam NC, Takayassu RN, Leme AA, Soares GP. Distance and protective barrier effects on the composite resin degree of conversion. Contemp Clin Dent. 2013;4(2):152-5. https://doi.org/10.4103/0976-237X.114845
73. Scott BA, Felix CA, Price RB. Effect of disposable infection control barriers on light output from dental curing lights. J Can Dent Assoc. 2004 Feb;70(2):105-10.
74. Strassler HE. Successful light curing - not as easy as it looks. Oral Health. 2013;103(1):18-26.

75. Price RB, Strassler HE, Price HL, Seth S, Lee CJ. The effectiveness of using a patient simulator to teach light-curing skills. J Am Dent Assoc. 2014;145(1):32-43. https://doi.org/10.14219/jada.2013.17
76. Ferracane J, Watts DC, Barghi N., Ernst CP, Rueggeberg FA, Shortall A et al. Effective use of dental curing lights: a guide for the dental practitioner. ADA Professional Product Review. 2013;8:2-12.
77. Turp V, Sen D, Poyrazoglu E, Tuncelli B, Goller G. Influence of zirconia base and shade difference on polymerization efficiency of dual-cure resin cement. J Prosthodont. 2011;20:361-5. https://doi.org/10.1111/j.1532-849X.2011.00721.x
78. Öztürk E, Chiang YC, Coşgun E, Bolay Ş, Hickel R, Ilie N. Effect of resin shades on opacity of ceramic veneers and polymerization efficiency through ceramics. J Dent, 2013;41 suppl 5:e8-14. https://doi.org/10.1016/j.jdent.2013.06.001
79. Runnacles P, Correr GM, Baratto Filho F, Gonzaga CC, Furuse AY. Degree of conversion of a resin cement light-cured through ceramic veneers of different thicknesses and types. Braz Dent J. 2014;25(1):38-42. https://doi.org/10.1590/0103-6440201302200
80. Ayres AP, Andre CB, Pacheco RR, Carvalho AO, Bacelar-Sá RC, Rueggeberg FA et al. Indirect restoration thickness and time after light-activation effects on degree of conversion of resin cement. Braz Dent J. 2015;26(4):363-7. https://doi.org/10.1590/0103-64402013x0024
81. Arrais CA, Giannini M, Rueggeberg FA. Effect of sodium sulfinate salts on the polymerization characteristics of dual-cured resin cement systems exposed to attenuated light-activation. J Dent. 2009;37(3):219-27. https://doi.org/10.1016/j.jdent.2008.11.016
82. Cavalcanti SC, Oliveira MT, Arrais CA, Giannini M. The effect of the presence and presentation mode of co-initiators on the microtensile bond strength of dual-cured adhesive systems used in indirect restorations. Oper Dent. 2008;33(6):682-9. https://doi.org/10.2341/08-18
83. el-Mowafy OM, Rubo MH, el-Badrawy WA. Hardening of new resin cements cured through a ceramic inlay. Oper Dent 1999;24(1):38-44.
84. Hofmann N, Papsthart G, Hugo B, Klaiber B. Comparison of photo-activation versus chemical or dual-curing of resin-based luting cements regarding flexural strength, modulus and surface hardness. J Oral Rehabil. 2001;28(11):1022-8. https://doi.org/10.1046/j.1365-2842.2001.00809.x
85. Braga RR, Cesar PF, Gonzaga CC. Mechanical properties of resin cements with different activation modes. J Oral Rehabil. 2002;29(3):257-62. https://doi.org/10.1046/j.1365-2842.2002.00821.x
86. Tanoue N, Koishi Y, Atsuta M, Matsumura H. Properties of dual-curable luting composites polymerized with single and dual curing modes. J Oral Rehabil. 2003;30(10):1015-21. https://doi.org/10.1046/j.1365-2842.2003.01074.x
87. Arrais CA, Rueggeberg FA, Waller JL, de Goes MF, Giannini M. Effect of curing mode on the polymerization characteristics of dual-cured resin cement systems. J Dent. 2008;36(6):418-26. https://doi.org/10.1016/j.jdent.2008.02.014
88. Schuchard A, Watkins CE. Thermal and histologic response to high-speed and ultrahigh-speed cutting in tooth structure. J Am Dent Assoc. 1965;71(6):1451-8. https://doi.org/10.14219/jada.archive.1965.0009
89. Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol. 1965;19(4):515-30. https://doi.org/10.1016/0030-4220(65)90015-0
90. Kwon SJ, Park YJ, Jun SH, Ahn JS, Lee IB, Cho BH et al. Thermal irritation of teeth during dental treatment procedures. Restor Dent Endod. 2013;38(3):105-12. https://doi.org/10.5395/rde.2013.38.3.105
91. Terranova PL. Adverse conditions found in the use of ultra high-speed equipment. N Y State Dent J. 1967;33(3):143-8.
92. Bhandary N, Desai A, Shetty YB. High speed handpieces. J Int Oral Health. 2014;6(1):130-2.
93. Hannig M, Bott B. In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources. Dent Mater. 1999;15(4):275-81. https://doi.org/10.1016/S0109-5641(99)00047-0
94. Briseño B, Ernst CP, Willershausen-Zönnchen B. Rise in pulp temperature during finishing and polishing of resin composite restorations: an in vitro study. Quintessence Int. 1995;26(5):361-5.
95. Al-Qudah AA, Mitchell CA, Biagioni PA, Hussey DL. Effect of composite shade, increment thickness and curing light on temperature rise during photocuring. J Dent. 2007;35(3):238-45. https://doi.org/10.1016/j.jdent.2006.07.012
96. 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):96-8. https://doi.org/10.1111/j.1600-0722.2004.00181.x
97. Baroudi K, Silikas N, Watts DC. In vitro pulp chamber temperature rise from irradiation and exotherm of flowable composites. Int J Paediatr Dent. 2009;19(1):48-54. https://doi.org/10.1111/j.1365-263X.2007.00899.x
98. Danesh G, Davids H, Duda S, Kaup M, Ott K, Schäfer E. Temperature rise in the pulp chamber induced by a conventional halogen light-curing source and a plasma arc lamp. Am J Dent. 2004;17(3):203-8.
99. Jakubinek MB, O'Neill C, Felix C, Price RB, White MA. Temperature excursions at the pulp-dentin junction during the curing of light-activated dental restorations. Dent Mater. 2008;24(11):1468-76. https://doi.org/10.1016/j.dental.2008.03.012
100. 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):485-90. https://doi.org/10.1016/j.jdent.2009.03.006

101. Park SH, Roulet JF, Heintze SD. Parameters influencing increase in pulp chamber temperature with light-curing devices: curing lights and pulpal flow rates. Oper Dent. 2010;35(3):353-61. https://doi.org/10.2341/09-234-L
102. Raab WH. Temperature related changes in pulpal microcirculation. Proc Finn Dent Soc. 1992;88 Suppl 1:469-79.
103. Kodonas K, Gogos C, Tziafas D. Effect of simulated pulpal microcirculation on intrapulpal temperature changes following application of heat on tooth surfaces. Int Endod J. 2009;42(3):247-52. https://doi.org/10.1111/j.1365-2591.2008.01508.x
104. Seltzer SE, Bender IB. The dental pulp. Philadelphia: J.B. Lippincott;1984. p. 195-7.
105. Goodis HE, Winthrop V, White JM. Pulpal responses to cooling tooth temperatures. J Endod. 2000;26(5):263-7. https://doi.org/10.1097/00004770-200005000-00001
106. Pohto M, Scheinin A. Microscopic observations on living dental pulp II. The effect of thermal irritants on the circulation of the pulp in the lower rat incisor. Acta Odontol Scand. 1961;16:315-7. https://doi.org/10.3109/00016355809064116
107. Brännström M, Lindén LA, Aström A. The hydrodynamics of the dental tubule and of pulp fluid. A discussion of its significance in relation to dentinal sensitivity. Caries Res. 1967;1(4):310-7. https://doi.org/10.1159/000259530
108. Uhl A, Mills RW, Jandt KD. Polymerization and light-induced heat of dental composites cured with LED and halogen technology. Biomaterials. 2003;24(10):1809-20. https://doi.org/10.1016/S0142-9612(02)00585-9
109. Weerakoon AT, Meyers IA, Symons AL, Walsh LJ. Pulpal heat changes with newly developed resin photopolymerisation systems. Aust Endod J. 2002;28(3):108-11. https://doi.org/10.1111/j.1747-4477.2002.tb00402.x
110. Nomoto R, McCabe JF, Hirano S. Comparison of halogen, plasma and LED curing units. Oper Dent. 2004;29(3):287-94.
111. Hofmann N, Hugo B, Klaiber B. Effect of irradiation type (LED or QTH) on photo-activated composite shrinkage strain kinetics, temperature rise, and hardness. Eur J Oral Sci. 2002;110(6):471-9. https://doi.org/10.1034/j.1600-0722.2002.21359.x
112. Hofmann N, Markert T, Hugo B, Klaiber B. Effect of high intensity vs. soft-start halogen irradiation on light-cured resin-based composites. Part I. Temperature rise and polymerization shrinkage. Am J Dent. 2003;16(6):421-30.
113. Jandt KD, Mills RW. A brief history of LED photopolymerization. Dent Mater. 2013;29(6):605-17. https://doi.org/10.1016/j.dental.2013.02.003
114. Leprince J, Devaux J, Mullier T, Vreven J, Leloup G. Pulpal-temperature rise and polymerization efficiency of LED curing lights. Oper Dent. 2010;35(2):220-30. https://doi.org/10.2341/09-203-L
115. Millen C, Ormond M, Richardson G, Santini A, Miletic V, Kew P. A study of temperature rise in the pulp chamber during composite polymerization with different light-curing units. J Contemp Dent Pract. 2007;8(7):29-37.
116. 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. https://doi.org/10.2341/13-068-L
117. Mouhat M, Mercer J, Stangvaltaite L, Örtengren U. Light-curing units used in dentistry: factors associated with heat development-potential risk for patients. Clin Oral Investig. 2017;21(5):1687-96. https://doi.org/10.1007/s00784-016-1962-5
118. Khaksaran NK, Kashi TJ, Rakhshan V, Zeynolabedin ZS, Bagheri H. Kinetics of pulpal temperature rise during light curing of 6 bonding agents from different generations, using light emitting diode and quartz-tungsten-halogen units: an in-vitro simulation. Dent Res J (Isfahan). 2015;12(2):173-80.
119. Kleverlaan CJ, de Gee AJ. Curing efficiency and heat generation of various resin composites cured with high-intensity halogen lights. Eur J Oral Sci. 2004;112(1):84-8. https://doi.org/10.1111/j.0909-8836.2004.00101.x
120. Runnacles P, Arrais CA, Pochapski MT, Dos Santos FA, Coelho U, Gomes JC et al. In vivo temperature rise in anesthetized human pulp during exposure to a polywave LED light curing unit. Dent Mater. 2015;31(5):505-13. https://doi.org/10.1016/j.dental.2015.02.001
121. Leonard DL, Swift EJ. Critical appraisal. Light-emitting-diode curing lights-revisited. J Esthet Restor Dent. 2007;19(1):56-62. https://doi.org/10.1111/j.1708-8240.2006.00065.x
122. Onisor I, Asmussen E, Krejci I. Temperature rise during photo-polymerization for onlay luting. Am J Dent. 2011; 24(4):250-6.
123. Yazici AR, Müftü A, Kugel G, Perry RD. Comparison of temperature changes in the pulp chamber induced by various light curing units, in vitro. Oper Dent. 2006;31(2):261-5. https://doi.org/10.2341/05-26
124. 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):254-9. https://doi.org/10.1002/jbm.b.30144
125. 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):50-5.
126. Tjan AH, Dunn JR. Temperature rise produced by various visible light generators through dentinal barriers. J Prosthet Dent. 1988;59(4):433-8. https://doi.org/10.1016/0022-3913(88)90038-8
127. Linsuwanont P, Palamara JE, Messer HH. An investigation of thermal stimulation in intact teeth. Arch Oral Biol. 2007;52(3):218-27. https://doi.org/10.1016/j.archoralbio.2006.10.009
128. Brännström M, Johnson G. Movements of the dentine and pulp liquids on application of thermal stimuli. An in vitro study. Acta Odontol Scand. 1970;28(1):59-70. https://doi.org/10.3109/00016357009033132

129. Dederich DN. Laser/tissue interaction: what happens to laser light when it strikes tissue? J Am Dent Assoc. 1993;124(2):57-61. https://doi.org/10.14219/jada.archive.1993.0036
130. Fodor L, Ullman Y, Elmann M. Aesthetic applications of intense pulsed light. Chapter 2: Light tissue interactions. London: Springer; 2011. p. 11-20.
131. Price RB, Murphy DG, Dérand T. Light energy transmission through cured resin composite and human dentin. Quintessence Int. 2000;31(9):659-67.
132. Nakajima M, Arimoto A, Prasansuttiporn T, Thanatvarakorn O, Foxton RM, Tagami J. Light transmission characteristics of dentine and resin composites with different thickness. J Dent. 2012;40 Suppl 2:e77-82. https://doi.org/10.1016/j.jdent.2012.08.016
133. Spranley TJ, Winkler M, Dagate J, Oncale D, Strother E. Curing light burns. Gen Dent. 2012;60(4):e210-4.
134. Maucoski C, Zarpellon DC, Lipppinski LC, Santos FA, Rueggeberg F, Arrais CA. Análise da temperatura do tecido gengival suíno exposto à luz LED polywave de alta potência. In: Proceedings of the 33nd SBPqO Annual Meeting; 2016 Sep 7-10; Campinas, SP. Braz Oral Res. 2016;30 Suppl 1:125.
135. Paul SJ, Leach M, Rueggeberg FA, Pashley DH. Effect of water content on the physical properties of model dentine primer and bonding resins. J Dent. 1999;27(3):209-14. https://doi.org/10.1016/S0300-5712(98)00042-6