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Light curing units and methods of polymerisation: A narrative review

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Abstract
Light-curing units (LCUs) are handheld dental devices that emit blue light (≈400–500 nm) to photopolymerize resin-based composites, adhesives, cements, and sealants. Modern LED LCUs, especially polywave types, are preferred for activating multiple photoinitiators efficiently. Effective curing depends on adequate radiant exposure (J/cm²), spectral match to the material, tip diameter, and proper technique, not just high irradiance.
Clinically, aim for at least 500–700 mW/cm² for ~20 s (≈10–14 J/cm²), with many operators using 1,200–1,500 mW/cm² for faster, reliable polymerization. Regular maintenance, tip cleaning, and periodic radiometer checks help ensure consistent performance and restoration longevity

Keywords: Polymerisation, light curing, shrinkage, wavelength

Introduction
Resin based restorative materials are the most essential component of restorative dentistry. Knowledge of the basics of any dental polymerisation mechanism is allows the clinician to have valuable information on differences among strategies manufactures use to optimize product performance, as well as factors under the control of clinician, by which they can influence the long-term outcome of their restorative procedures. Understanding the concepts of polymerisation shrinkage and different methods to minimize them, increases the quality of restoration

Polymerisation
Most resin-based dental materials use methacrylate monomers that polymerise through vinyl free-radical addition polymerisation. Methacrylate monomers contain a carbon–carbon double bond that participates in the polymerisation reaction. Different substituent groups produce monomers with different properties. Examples include methyl methacrylate, ethyl methacrylate, HEMA, Bis-GMA, TEGDMA, and UDMA. Monomers containing two methacrylate groups are known as dimethacrylates and form cross-linked polymer networks.
The addition-polymerisation process consists of four stages:
- Induction.
- Propagation.
- Chain transfer.
- Termination.

Induction
Induction involves activation and initiation. A free-radical source is required to begin polymerisation. Free radicals may be produced by chemical activation, heat, visible light, ultraviolet light, or energy transfer from another compound. In dentistry, chemical activation, heat, and visible light are the most commonly used methods.

During initiation, the activated initiator forms a free radical that attacks the carbon–carbon double bond of a monomer. This creates a new free radical at the end of the monomer molecule, allowing the chain reaction to proceed.

Propagation
During propagation, the free radical formed during initiation reacts with another monomer. The resulting dimer remains reactive and attacks additional monomer molecules. This process continues repeatedly, resulting in the growth of a polymer chain.
Polymerisation occurs rapidly and is accompanied by the release of exothermic energy. The rate and extent of chain growth depend on the number of available monomers, the concentration of free radicals, temperature, light exposure, and the composition of the resin.

Termination
Polymerisation ends when the reactive free-radical centres are destroyed. Termination generally occurs by:
- Direct coupling of two growing polymer chains.
- Transfer of a hydrogen atom from one chain to another.

In direct coupling, two polymer chains combine through the formation of a covalent bond. In hydrogen transfer, one growing chain donates a hydrogen atom to another, resulting in the formation of a stable chain and an unsaturated bond.

Dental photocuring
Dental photocuring depends on the interaction between light photons and photoinitiator molecules. The photoinitiator absorbs light of a specific wavelength and becomes excited. It then forms free radicals that initiate polymerisation.
Electromagnetic radiation travels as sinusoidal waves. Its important characteristics include:
- **Frequency:** the number of waves passing a point per second.

- **Wavelength:** the physical distance between corresponding points on successive waves.

- **Energy:** related inversely to wavelength; shorter wavelengths generally contain more energy.

Photocuring differs from chemical curing because light-cured materials depend on the penetration of photons into the restoration. Chemical activation produces free radicals throughout the bulk of the material, whereas light activation is limited by light absorption and scattering.

Ultraviolet curing

Ultraviolet curing was introduced into dentistry after its use in the printing industry. Early dental systems used ultraviolet light at approximately 365 nm to activate urethane methacrylate restoratives and sealants.

Although these materials could produce durable restorations, clinical use was limited because:

- Increments had to be less than approximately 1 mm thick.
- Each increment required a long exposure.
- Curing was slow and technique-sensitive.
- Continuous operation reduced bulb output.
- Ultraviolet radiation posed risks such as ocular damage and possible changes in oral microflora.

Consequently, dental curing systems shifted toward visible light, generally within the 380–700 nm range.

Visible light curing

Visible light initiates polymerisation when photons are absorbed by photoinitiator molecules. The absorbed energy elevates an electron to an excited state. The excited photoinitiator either reacts with an amine co-initiator or decomposes directly to form free radicals.

Photoinitiators may be classified as:

- **Type I:** directly produce free radicals after light absorption.
- **Type II:** require interaction with a co-initiator, usually a tertiary amine.

The degree of polymerisation depends on the quantity and rate of free-radical formation. The light must possess a suitable wavelength and sufficient radiant energy to activate the photoinitiator throughout the restoration.

Dental visible light photoinitiators

Camphorquinone

Camphorquinone is the most widely used dental photoinitiator. It is a Type II initiator and functions with a tertiary amine. Its principal absorption range is approximately 425–495 nm, with peak activity around 468–470 nm.

The disadvantages of camphorquinone include:

- Relatively slow and less photon-efficient initiation.
- Dependence on an amine co-initiator.
- A yellow colour that may affect the final shade of the restoration.

The development of tooth bleaching increased the demand for very light-coloured restorative materials. This encouraged manufacturers to reduce camphorquinone concentration or combine it with alternative photoinitiators.

Lucirin TPO

Lucirin TPO is a Type I photoinitiator that absorbs mainly in the violet region, approximately 390–410 nm. It is highly efficient and can reduce the yellow appearance associated with camphorquinone. It is now often combined with camphorquinone and other photoinitiators rather than used alone.

PPD

PPD, or 1-phenyl-1,2-propanedione, is a Type II photoinitiator with an absorption range of approximately 390–460 nm. It is commonly combined with camphorquinone to improve polymerisation and reduce yellow colour. The combined system may produce a synergistic effect and moderate the rate of polymerisation.

Ivocerin

Ivocerin is a dibenzoyl germanium derivative and a Type I photoinitiator. It absorbs over a broad short-wavelength range, approximately 390–445 nm. It is available only in selected materials and can improve curing, particularly when used with other photoinitiators.

Because different photoinitiators absorb different wavelengths, curing lights must provide an appropriate spectral range. A light with high intensity but an unsuitable wavelength may fail to adequately cure a material.

Visible curing lights

Quartz-tungsten-halogen lights (QTH)

QTH curing lights use a tungsten filament enclosed in a quartz casing containing halogen gas. Electrical resistance heats the filament, producing electromagnetic radiation. Most of the emitted energy is infrared and must be filtered to prevent excessive heat and to remove wavelengths that are unnecessary for polymerisation.

QTH units commonly included:

- Hand-held gun-shaped designs.
- Cooling fans.
- Replaceable fibre-optic light guides.
- Infrared and visible-light filters.
- Adjustable exposure times.

Typical exposure times for a 2-mm composite increment were approximately 40–60 seconds. Turbo-tips were developed to increase irradiance by reducing the diameter of the light-emitting end. However, they produced a narrow beam, requiring overlapping exposures.

High-intensity QTH units introduced concerns about rapid polymerisation, increased internal stress, marginal gaps, and thermal injury. To address these problems, soft-start systems were developed, including:

- Step curing.
- Ramp curing.
- Pulse-delay curing.

QTH lights produce a broad spectrum and can activate several photoinitiators. They are particularly effective for camphorquinone because their emission overlaps its absorption range. Their disadvantages include bulb ageing, heat generation, limited efficiency, and the need for regular maintenance.

Plasma-arc lights (PAC)

PAC lights use two tungsten electrodes enclosed in high-pressure xenon gas. A high-voltage spark produces intense

radiation across a broad range, including infrared, visible, and ultraviolet wavelengths. Extensive filtering is necessary to deliver clinically useful light.
Early PAC units provided very short exposures, sometimes 1–3 seconds. However, the short exposure was partly due to the limited duration for which the spark could be maintained, rather than superior curing efficiency.
Later PAC systems incorporated electronic control and allowed longer exposures. Approximately 10 seconds was often required to cure a 2-mm increment, although the time depended on the composite brand and shade.
PAC lights produce broad-spectrum radiation and can activate several photoinitiators. Their disadvantages include:

- High heat generation.
- Expensive and complex construction.
- Potential for excessive polymerisation stress.
- Confusion regarding the wavelength requirements of different materials.

Argon-ion lasers
Argon-ion lasers were introduced initially for tooth bleaching and later used for resin curing. They were large, expensive, and generally unsuitable for routine dental practice.
Their emission spectrum overlapped well with camphorquinone but did not adequately activate TPO and only partially activated PPD. As alternative photoinitiators became more common, the clinical usefulness of argon-ion lasers decreased.

Light-emitting diodes
Background
LED curing lights use semiconductor technology. When electrons cross a semiconductor energy gap, light is emitted at a wavelength determined by the material's composition.
LEDs offer several advantages:

- High energy efficiency.
- Low power consumption.
- Minimal infrared emission.
- No filament.
- No requirement for extensive optical filtering.
- Long service life.
- Battery-powered operation.
- Compact design.

First generation
Early blue LED units used multiple low-output LED elements arranged in arrays. A turbo-tip was often required to increase irradiance. These units were effective mainly for camphorquinone-containing materials and generally required longer exposures.
Their limitations included:

- Low individual LED output.
- Heat generation within closely packed arrays.
- Limited battery technology.
- Inability to activate some alternative photoinitiators, particularly TPO.
- Inconsistent irradiance among different models.

Second generation
Second-generation LEDs used high-output chips developed for illumination applications. These provided much greater photon density, especially in the camphorquinone absorption range of approximately 460–480 nm. As a result, curing times were reduced.
Improvements included:

- Higher irradiance.
- More efficient curing.
- Longer-lasting nickel-metal-hydride batteries.
- Improved heat sinks.
- Greater suitability for high-intensity curing.

However, many second-generation blue LEDs still did not adequately activate TPO or Ivocerin.

Third generation
Third-generation LEDs use multiple chips that emit blue and violet light. They are designed to activate several photoinitiators, including camphorquinone, PPD, TPO, and Ivocerin.

Different designs may include

- A central blue LED surrounded by violet LEDs.
- Multiple blue and violet chips.
- Blue emissions near 445 and 460 nm combined with violet emission near 400 nm.

These polywave units provide broader spectral coverage. However, distributing energy across several wavelengths may reduce the blue intensity available for deep camphorquinone activation. They are most advantageous for materials containing multiple photoinitiators.
Third-generation lights are available in gun-shaped and pencil-shaped designs. Some place the LED chips directly at the tip, improving access and reducing light transmission losses through fibre-optic guides. Lithium-ion batteries are now commonly used because they provide stable and prolonged operation.

Curing shrinkage and curing stress
Polymerisation shrinkage occurs because monomers occupy less free space after conversion into a polymer. The volume occupied by the polymer may be approximately 20% lower than the free volume between unreacted monomers.
Shrinkage produces stress after the material reaches the gel point. Once the resin becomes rigid, flow is limited and the developing stresses are concentrated at the tooth–composite interface. These stresses may cause:

- Bond failure.
- Marginal gaps.
- Microleakage.
- Marginal staining.
- Secondary caries.
- Postoperative sensitivity.
- Cusp deflection or enamel damage.

The main factors affecting shrinkage and stress are:

1. Composite volume.
2. Composite composition.
3. Polymerisation rate.
4. Ratio of bonded to nonbonded surfaces, known as the C-factor.

Larger monomers such as Bis-GMA and UDMA reduce shrinkage because they contain fewer reactive double bonds per unit of mass than smaller monomers. Inorganic fillers also reduce shrinkage because they do not polymerise.

Nevertheless, even modern composites can produce clinically significant shrinkage stress.

Reduction of Shrinkage Stresses

Light-activated resins offer better working-time control, improved colour stability, and less porosity than chemically activated systems. However, chemically cured materials may experience less residual stress because their slower reaction permits more flow before gelation. Internal pores formed during mixing may also help relax stress.

Two broad strategies are used to reduce polymerisation stress:

1. Modify the resin chemistry or composition to reduce volume contraction.
2. Use clinical placement and curing techniques that reduce the effects of shrinkage.

Chemical modification is the preferred long-term approach. Clinically, incremental placement and controlled curing remain important methods.

Incremental Buildup and Cavity Configuration

The C-factor is the ratio of bonded to nonbonded surfaces. A high C-factor restricts flow and increases polymerisation stress. During curing, bonded surfaces remain attached to the cavity walls, while free surfaces can contract and partially relieve stress.

Incremental placement reduces stress by:

- Decreasing the volume of each increment.
- Reducing the effective bonded surface area.
- Increasing the proportion of free surfaces.
- Improving light penetration and depth of cure.

Incremental layering also addresses the limited depth of cure of light-activated composites. Its disadvantages are increased placement time, greater technique sensitivity, and the possibility of incorporating voids between increments.

Different curing methods

Modern composites are suitable for both anterior and posterior restorations because of improvements in filler technology, resin chemistry, and mechanical properties. They are also used for orthodontic bracket bonding. Light-cured systems are increasingly preferred because they provide controlled working time and avoid air incorporation associated with mixing chemically cured materials.

The clinician must ensure that sufficient light reaches the entire composite increment. Inadequate polymerisation compromises hardness, strength, wear resistance, colour stability, and longevity.

Continuous curing technique

Polymerisation shrinkage causes contraction stress and may disrupt the marginal seal. Continuous and modified curing techniques have been developed to reduce this effect.

Uniform Continuous Cure

A light of constant intensity is applied for a predetermined period. This is the conventional technique used with QTH and LED curing units. It is simple and predictable when the light output, exposure time, increment thickness, and tip position are appropriate.

Step Cure

In step curing, the composite is initially exposed to low-intensity light and then to higher intensity. The initial low-energy phase allows the material to remain in a more flexible gel state, permitting some flow and stress relaxation before final curing.

Advantages include:

- Reduced initial polymerisation stress.
- Potentially improved marginal adaptation.
- Reduced marginal contraction.

A disadvantage is that the surface nearest the light may become more highly cured than deeper regions. Traditional step-curing systems were mainly available with halogen lamps.

Ramp Cure

In ramp curing, light intensity gradually increases from a low level to a high level. The slower initial reaction permits resin flow and reduces early stress formation. It may also promote the development of longer polymer chains and a more stable polymer network.

Very high energy delivered over a short period may produce shorter polymer chains, increased brittleness, and greater shrinkage. Ramp curing was mainly associated with halogen systems, although it could be performed manually by gradually moving a conventional light closer to the restoration.

High Frequency Pulse Cure

High-frequency pulse curing applies a brief, very high-intensity exposure, commonly for approximately 10 seconds. The intensity may be several times greater than that of conventional curing.

Potential concerns include:

- Formation of short polymer chains.
- Reduced tensile strength.
- Increased brittleness.
- Increased polymerisation stress.

This method has been associated with argon lasers, plasma-arc lights, and high-intensity third-generation LEDs.

Intermittent curing technique

Intermittent or discontinuous curing, also called soft curing, begins with a low-intensity exposure. This allows the composite to polymerise slowly and flow from unbonded surfaces toward bonded cavity walls. A subsequent high-intensity exposure completes polymerisation.

The technique aims to reduce:

- Polymerisation stress.
- Marginal gaps.
- Interfacial defects.
- Disruption of the marginal seal.

Pulse Delay Cure

Pulse-delay curing consists of:

- A short, low-intensity light exposure.
- A waiting period.
- A longer, higher-intensity final exposure.

The first pulse initiates polymerisation while allowing the composite to undergo some stress relaxation. During the delay, the material becomes sufficiently rigid to limit further marginal movement. The second exposure completes polymerisation.

An example involved an initial 3-second exposure at approximately 200 mW/cm², followed by a delay of several minutes and a final 30-second exposure at approximately 600 mW/cm².

Contemporary Advances—Room for Improvement

Modern high-intensity LED curing lights are widely marketed with very short curing times. However, some inexpensive or untested units may have:

- Poor beam uniformity.
- Small effective optical footprints.
- Unstable output during exposure.
- Inadequate battery compensation.
- Insufficient spectral coverage.
- Hot and cold spots within the beam.

A curing light may appear bright but still fail to deliver adequate radiant energy to all regions of the restoration. Manufacturers should provide information regarding total radiant power, spectral distribution, beam uniformity, and output stability.

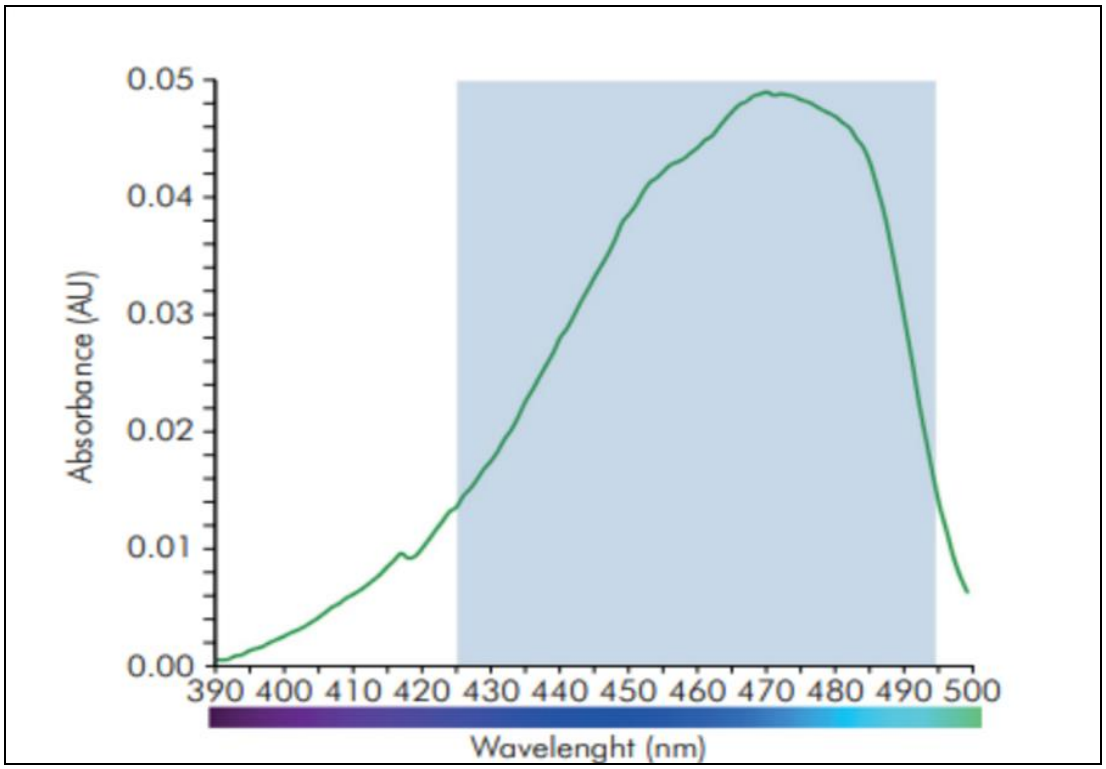

Fig 1: Visible light absorption spectrum of camphoroquinone, ranging from about 425 to 495nm.

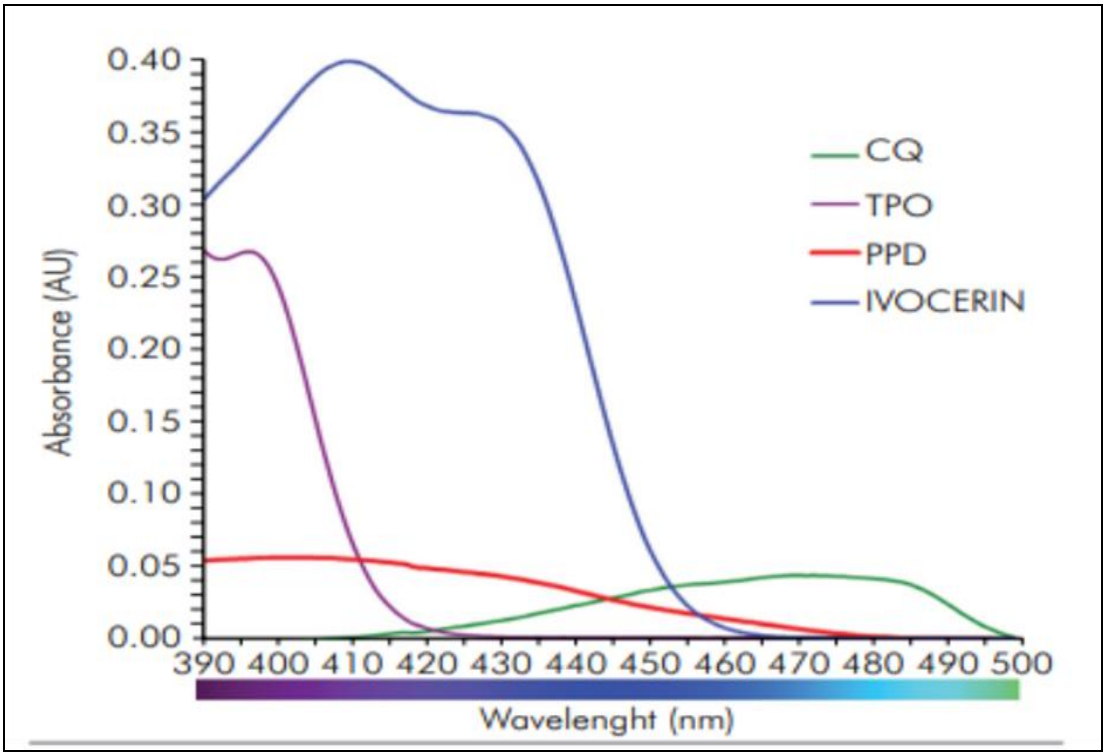

Fig 2: Difference in spectral absorption profiles and absolute absorption values among dental photo initiators, when present at similar molar concentrations

Fig 3: Internal components of a typical QTH curing light

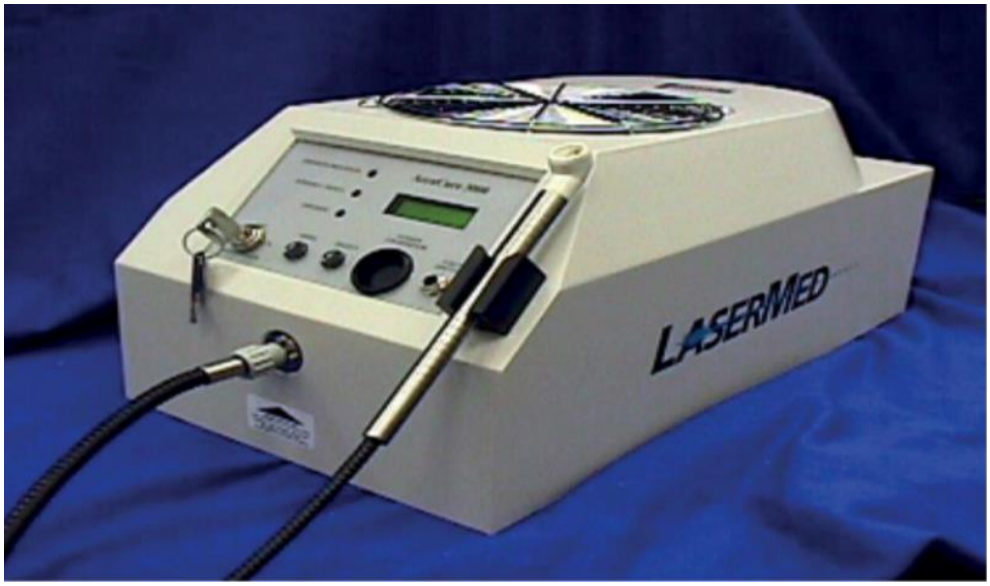

Fig 4: Argon-ion dental light-curing laser

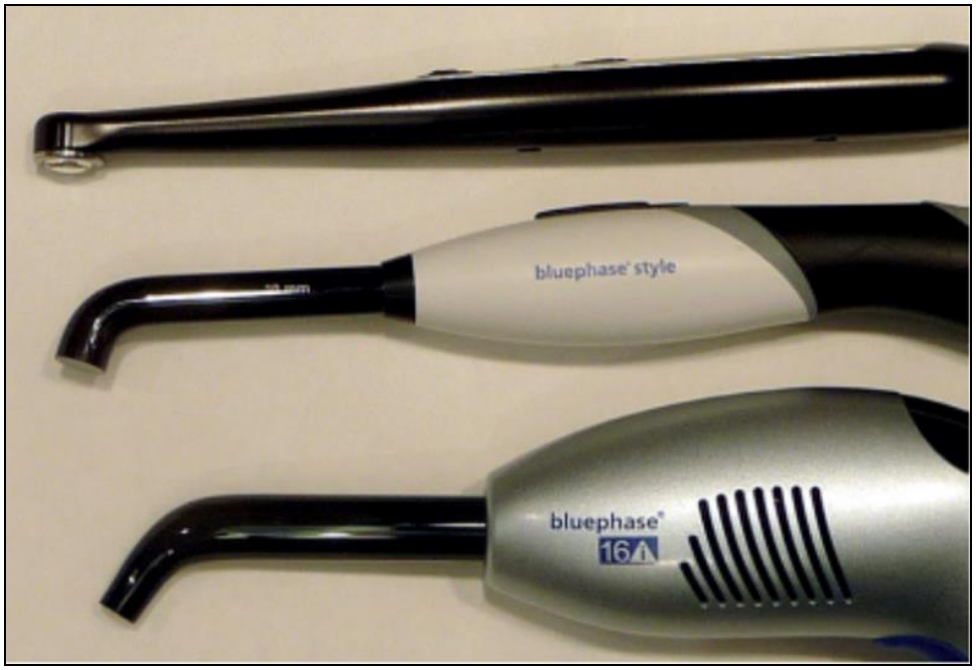

Fig 5: A variety of form factors of LED curing lights.

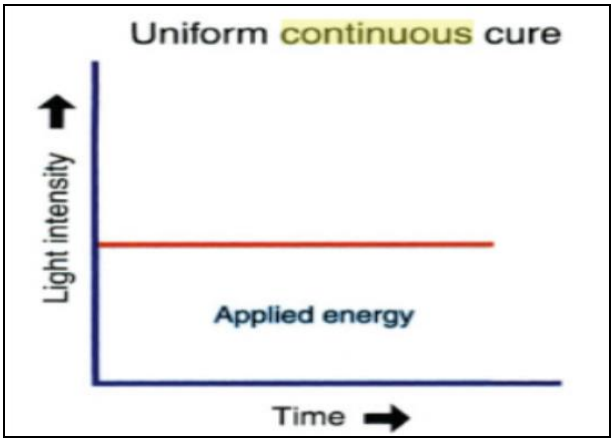

Fig 6: Uniform continuous cure

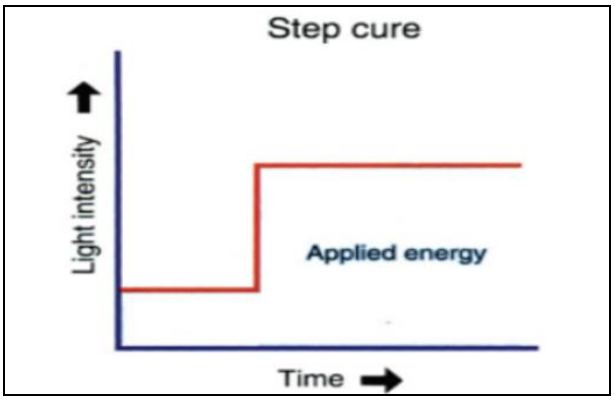

Fig 7: Step cure.

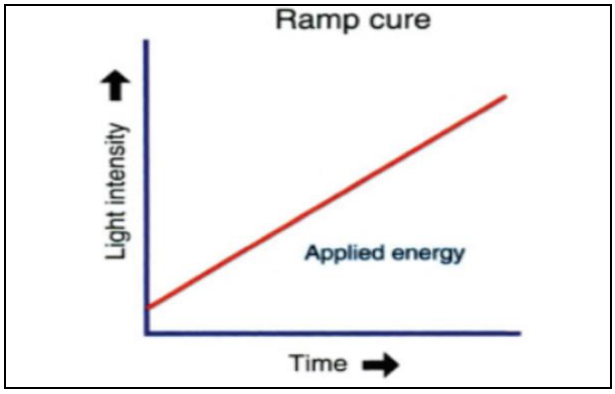

Fig 8: Ramp cure

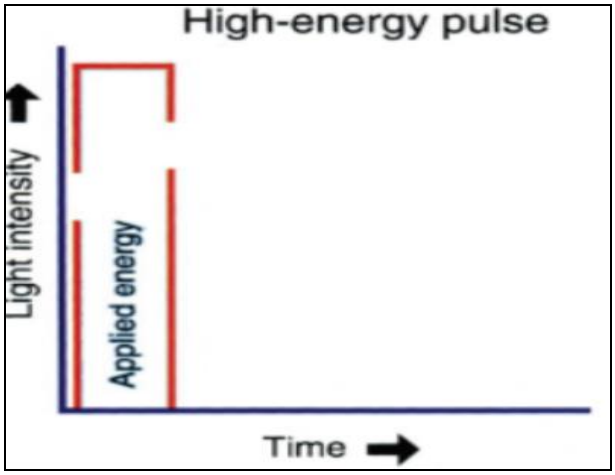

Fig 9: High-energy pulse

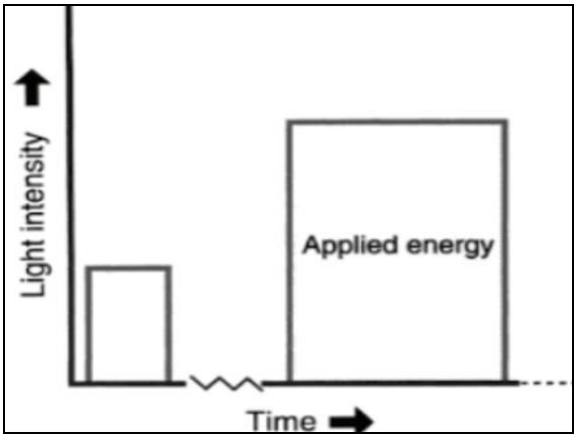

Fig 10: Pulse delay cure

Conclusion

Successful polymerisation depends on both the chemistry of the resin and the quality of light delivered to it. The commonly reported irradiance at the light tip does not necessarily represent the light received by the restoration because distance, beam divergence, beam uniformity, wavelength, and restoration thickness influence the actual radiant energy reaching the composite.

Inadequate curing may result from insufficient intensity, unsuitable wavelength, excessive tip-to-restoration distance, poor beam coverage, contamination, ageing of the curing unit, or insufficient exposure time. Clinicians should use a suitable curing light, place the tip close and perpendicular to the restoration, follow material-specific exposure recommendations, use appropriate increments, and monitor the light regularly.

Manufacturers and researchers should report:

1. Radiant power throughout the exposure cycle and spectral radiant power according to wavelength.
2. Beam profile and spectral emission across the entire light beam.
3. The actual light received by the resin-based restorative material rather than only the

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