**Bruno Pelissier**

**Bruno Jacquot, Will M Palin and Adrian C Shortall**

# Three Generations of LED Lights and Clinical Implications for Optimizing their Use. 1: From Past to Present

**Abstract:** In the present era of adhesive dentistry light-curing units are essential pieces of surgery equipment for everyday practice. The success and longevity of light-activated resin sealants, photo-cured restorations and orthodontic treatments are related to the efficacy of the light-curing process. Energy efficient blue LED lights are rapidly replacing their halogen lamp predecessors as the standard light source. Manufacturers are producing materials with different initiators and not all of these materials can be properly polymerized with blue LED lights.

**Clinical Relevance:** Adequate curing in depth is basic to the long-term clinical success of any light-activated restoration. As dentists enter the post-amalgam era they are required to restore increasingly large cavities with direct resin composite. To achieve this goal predictably, an appropriate light source needs to be combined with materials knowledge, requisite clinical skills and attention to detail throughout the entire restoration process.

**Dent Update 2011; 38: 660–670**

The goal of adhesive restorative dentistry is smaller restorations of increased longevity. Advances in adhesion and polymerization, coupled with new materials and conservative or 'minimal intervention' restorative treatments, have revolutionized dental practice since the introduction of light-cured composites on to the market 35 years ago (Figures 1 and 2). The curing light is just one aspect of a proper clinical polymerization protocol. Operator proficiency, the composite material formulation (shade and opacity, initiator system, resin matrix composition, filler type and loading, etc), the adhesive system and the polymerization method all have a strong influence on the outcome. The aims of dental photocuring are to gain uniform high conversion to full depth in the fastest appropriate radiation time whilst minimizing conversion shrinkage stress and material/tooth/tissue overheating effects. For optimal results, the appropriate radiation time for a specific situation depends on the material (product, shade, opacity) and the light source parameters as well as, for example, clinical (cavity location, access, depth) and operator variables.

**B Pelissier**, BDS, PhD, **B Jacquot**, BDS, PhD, UFR d'Odontologie de Montpellier I 545, avenue du Professeur Jean-Louis Viala 34193, Montpellier Cedex 5, France, **WM Palin**, BSc, PhD, **AC Shortall**, BDS, DDS, The Dental School, University of Birmingham, St Chad's Queensway, Birmingham B4 6NN, UK.

Light activation or 'curing' units (LAUs), as they are commonly referred to, have evolved tremendously since the first commercially available 50W mercury arc lamps were marketed, which emitted light around 365 nm for polymerizing UV light-activated fissure sealants and composites. These units were bulky, had to be allowed to 'warm-up' and typically produced very low irradiance levels between 10–50 mW/cm$^2$, with most of the light output concentrated in a 'horseshoe-shaped band over the face of the light guide exit window' or tip.[1] In addition, they suffered degradation of light output during their lifespan; UV-cured composites were capable of high conversion levels and good clinical longevity but had very limited cure depths.[2]

Concerns over UV irradiation of soft tissues, together with a high incidence of clinical failures in comparison to their chemically initiated counterparts,[3] led to these materials being replaced by 'white or blue' light-activated, light-cured composites, introduced in 1978.

Forty seconds curing at a minimum irradiance of 250–400 mW/cm$^2$ per 2 mm increment (10 to 16 J/cm$^2$ radiant exposure) was required for adequate polymerization of blue light-activated composites, depending on product.[4] Unfortunately, QTH LAUs suffer from bulb,

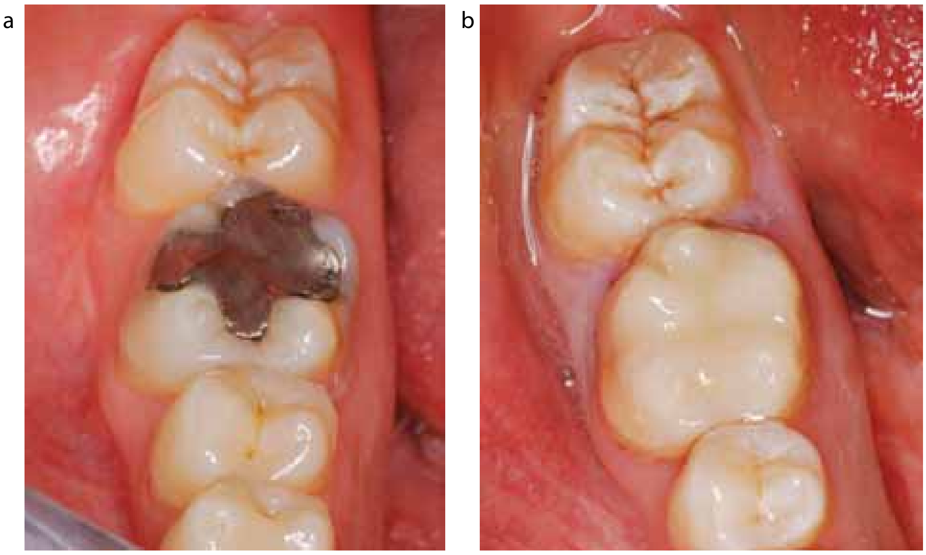

**Figure 1. (a, b)** Posterior composite restoration (g-aenial® GC dental): pre- and post-operative views.

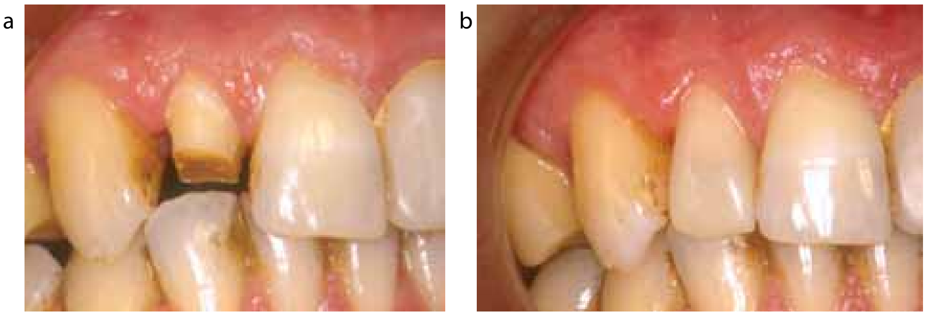

**Figure 2. (a, b)** Anterior composite restoration (Herculite XRV® Kerr Inc): pre- and post-operative views.

filter and reflector deterioration in service as units age. Furthermore, damage may occur and debris accumulates on light guide exit windows or tips. Studies published between 1994 and 2009 revealed that approximately 50% of LAUs did not meet minimum irradiance requirements and the practitioners were largely unaware of the problem! This may be one reason why many light-activated restorations have a shorter than wished for service life. Whilst one investigation in Texas[5] which revisited the dental offices a decade after the initial survey reported an overall improvement in the situation, presumably partly due to the purchase of new LAUs, the most recent study from dental offices in the Maharashtra region of India has revealed a more disquieting picture.[6] This latter study reported that, of 119 quartz-tungsten-halogen (QTH) and 81 light-emitting-diode (LED) LAUs surveyed, only 10% of the LED units and 2% of the QTH units had irradiances >400 mW/cm$^2$ and most units had composite resin build-up on the tips. QTH LAUs became the mainstay of dental practice until the last decade, when more effective LED LAUs became available.[7] Blue light LED LAUs are much more energy efficient and compact compared with their QTH predecessors, and offer stable output over the full discharge cycle of the battery, unlike their bulky cordless QTH predecessors.[8] Significantly more of the radiant energy produced by blue LED LAUs lies within the absorption spectrum of camphorquinone (CQ), the commonest dental photo-initiator.[9] QTH LAUs have a bulb lifetime of 50–100 hours, typically, whilst high quality LED LAUs should last for thousands of hours if operated and cared for according to manufacturer's guidelines. Halogen and plasma-arc units have limited bulb lifespans and, after several thousand restorations (say five irradiation cycles per restoration on average), the output of a halogen lamp may have declined to 50% or less of its original level, whilst a plasma-arc unit may have lost 40% of its useful irradiance over the same time period. Plasma-arc units and argon lasers have become obsolete with the introduction of high power LED LAUs. Diode-pumped solid state (DPSS) lasers hold promise because of their unparalleled energy efficiency but significant issues remain to be addressed before they will be marketable.

The optical power output of a dental light-curing source determines its effectiveness in conjunction with the extent of spectral wavelength matching with the absorption spectrum of the photo-initiator present in the light-curing resin. The radiometric unit of power is the Watt. This is not the most important parameter to characterize the efficiency of a curing light. More than the quantity of the light emitted, the most important factor is what is frequently referred to as its 'intensity', ie the surface area on to which the light falls which is flux per solid angle. The term 'intensity' only has meaning when the light source is very small relative to the distance from the 'target'. Here the light may be considered as a point source and the 'power density' or, more accurately, the irradiance (power per unit area) declines with the square of the distance from the source. This occurs in 'far field' when the distance from the target to the source is at least 5 to 10 times the source diameter. The term 'intensity' is ambiguous and should not be used without qualifiers. Radiant incidence or 'Irradiance' is flux per unit area impinging on a source. Irradiance says nothing about the direction from which the light is hitting the surface. The radiometric unit is 'Watts per square metre or square centimetre'. Manufacturers use milliwatts per square centimetre as the unit of reference to qualify their devices. To calculate this they use the emitted power divided by the active surface area of the light guide, but this value for irradiance only has value when the distance between the light source exit window and the 'target' is very small. In this case, the manufacturer's stated irradiance value should be valid. Unfortunately, for dental LAUs irradiance declines rapidly with source distance (Figure 3). Radiant exposure (reported in units of J m$^{-2}$) is defined as the time integral of the irradiance. It is often expressed (incorrectly) as energy density. The term energy density should be reserved for describing the volumetric energy deposition and has units of J m$^{-3}$.

Dental researchers, light manufacturers and distributors frequently measure the output power of their dental

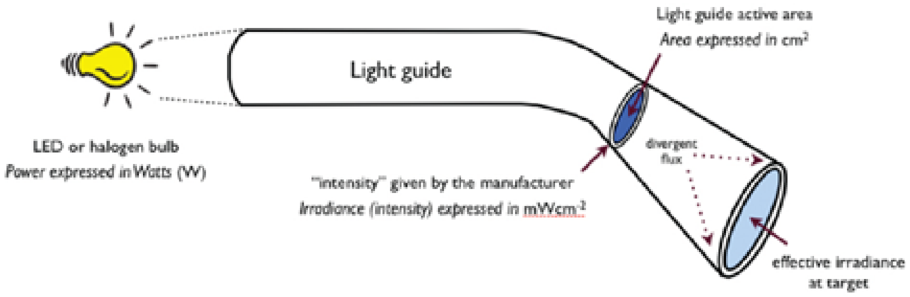

**Figure 3.** Light activation or 'curing' unit.

lights with hand-held 'curing radiometers'. At best they are imprecise measuring instruments (mW/cm$^2$) and their values are subject to large inter- and intra- unit differences in readings.[10] The value they yield depends on many factors, including the exit diameter of the light source relative to the unit sensor window, thus different readings may be expected from the same light source with different diameter light guides.[11] The detector has to be smaller than the light source 'tip' for the radiometer to work and this means that the dental radiometer is not exposed to the total power from the light source. It also assumes that the light emission is evenly spread across the light source exit window face and this does not occur. Manufacturers may optimize dental radiometers to their own brand of LAUs. Hand-held radiometers give no information about the spectrum or true irradiance of the light source, which may vary considerably even between blue LED light units of the same model from a single manufacturer. This depends on how tightly the dental LAU manufacturer requests the LEDs to be 'binned' by the supplier in terms of spectral bandwidth and power.

Increasingly, researchers and manufacturers of high quality LCUs employ expensive laboratory-based optical devices (integrating spheres which capture all the emitted light and are linked to spectroradiometers and/or benchtop power meters which can be annually recalibrated by a certified body according to international standards) for measuring the irradiance and spectral characteristics of their LAUs. Having determined the total spectral flux of the LAU, the surface area of the 'optically active' or unclad part of the light guide or tip or exit window is determined in order to determine the true irradiance value (sometimes referred to as 'power density'). Test equipment is calibrated each time before measuring the spectral flux at the wavelength emitted by the LED since a 5 nm variation can lead to a 5% measurement inaccuracy. Unfortunately, the majority of dental research papers continue to base their findings and conclusions on hand-held dental radiometer readings!

## History of blue LED light-curing unit development in dentistry

### The pioneers

Blue electroluminescence from a silicon carbide crystal LED source was reported by Round in 1907.[12] The initial studies on LEDs started in the 1960s with the first combinations of gallium, arsenic and phosphorus (GaAsP). This set-up produced very weak emissions in the red spectrum (with a wavelength around 655 nm). In 1962, the invention of a synthetic red LED provided a new type of light that was robust, efficient and suitable for portable battery powered operation. Research into LEDs emitting in the blue spectrum (colour corresponding to the wavelength for curing dental composites) started to bear fruit at the end of the seventies, but it was not until 1991 that a bright blue LED was created and, in 1995, blue LEDs producing 4.8 mW were reported, representing more than a 600-fold increase in power compared with silicon carbide technology.[13] We are indebted to the Canadian J. Kennedy for the first description of a light-curing device using a source with LEDs that could be employed in dentistry. There was a series of patents, the first dating from 13 September 1993.[14] Its description is so precise and predictive that it feels as if one is actually holding a first-generation light. The first publication on the subject in wide-circulation dental journals comes from Robin W Mills and dates from March 1995, whilst Kennedy's patent was not accessible to the public.[15] Presumably, Mills was not familiar with Kennedy's work when he wrote his letter 'Blue light emitting diodes – another method of light curing?' to the editor of the *British Dental Journal*. In a study published in 1996, Fujibayashi *et al*[16] described a blue light source, produced by 61 LEDs, with a typical peak wavelength of 450 nm, focused with a lens yielding a spot size of 8 mm. The irradiance of this unit was 100 mW/cm$^2$ and it matched the cure depth and Knoop hardness of a QTH LAU of the same irradiance.[16] In a follow-up study published two years later they improved the performance of their experimental LED light using diodes of typical peak wavelength around 470 nm. The first full UK-based research investigation was by a group working in Scotland. Whitters, Girkin and Carey[17] published in *Optics Letters* work which used a basic six InGaN LED device which they reported cured composites more quickly than a conventional QTH source but with a lower material temperature rise during cure. Three months later the Bristol group of Mills, Jandt and Ashworth published the first of a series of investigations in dental and scientific journals into LED light curing.[18] Their paper reported in the *British Dental Journal* that an LED LAU with 64% the irradiance of a QTH LAU achieved significantly greater cure depths with three commercial composites. After one or two years of calm, everything happened very quickly. Yet, in 2002, some specialists in dental composites were calling for caution regarding LED LAUs and still predicting a long life for halogen lamps! Halogen lamps are rapidly becoming obsolete as international bodies outside dentistry seek to ban and replace them with more energy efficient sources. This technological tidal wave towards LED light curing, rarely seen in dentistry, can now be divided into four time periods or generations.

## First-generation LED lights (1999–2002)

Early LED units were low powered (<1 Watt total output from a 7–19 diode array) with relatively low irradiance levels (range 100–280 mW/cm$^2$) requiring prolonged radiation times of up to 60 s for a 2 mm increment. They had a very narrow spectral range which was ideal for camphorquinone (CQ) initiated, resin-based-composites (RBCs). The best known during this period were the

**Figure 4**. The LUXoMAX® (Akeda): first-generation low power blue LED LAU.

LUXoMAX® (Akeda, Lystrup, Denmark) which was the first commercial dental LED LCU to appear on the UK market (Figure 4) in 2000, Elipar$^{TM}$Freelight from 3M ESPE (Weybridge, Surrey), Starlight® from Mectron (Plandent Ltd, Stevenage, Herts), Aqua Blue® from Toesco (NY 11021, USA) and CoolBlu® from Dental Systems (Ormond Beach, FL 32175, USA). The major technical characteristics of these small portable units were their use of between 7 and 19 low-energy LEDs, a battery with a good run time and an absence of heat and hence no need for a fan. The unit, which dominated the LED market at the time, was the Freelight, which provided an irradiance of 250–280 $mW/cm^2$, making it comparable to approximately 400 $mW/cm^2$ irradiance QTH lamps in terms of efficiency because of its superior spectral absorption match with the CQ initiator. First-generation LED technology was not powerful or reliable enough to survive in daily dental practice. Relatively long irradiation time menus (from 15 to 60 seconds) attempted to compensate for deficiencies, but this nevertheless failed to yield the expected curing results and it soon became apparent that these lights had insufficient power. Only the GC-e® light unit (GC), comprising 64 LEDs, managed to rival the halogen lamps used at the time, approaching 500 $mW/cm^2$. Unfortunately, this innovative unit arrived on the market too early and, having 11 possible cure modes, added unnecessary operational complexity (Figure 5). Producing grid-like arrays of many low power LEDs focused on to a small area was a major achievement but increased handpiece bulk (Figure 5) and led to manufacturing challenges. The GC-e® light (Figure 6) and the more powerful (400 $mW/cm^2$) single one Watt chip LED Freelight replacement for its 19 diode namesake were links between the first and second generations.

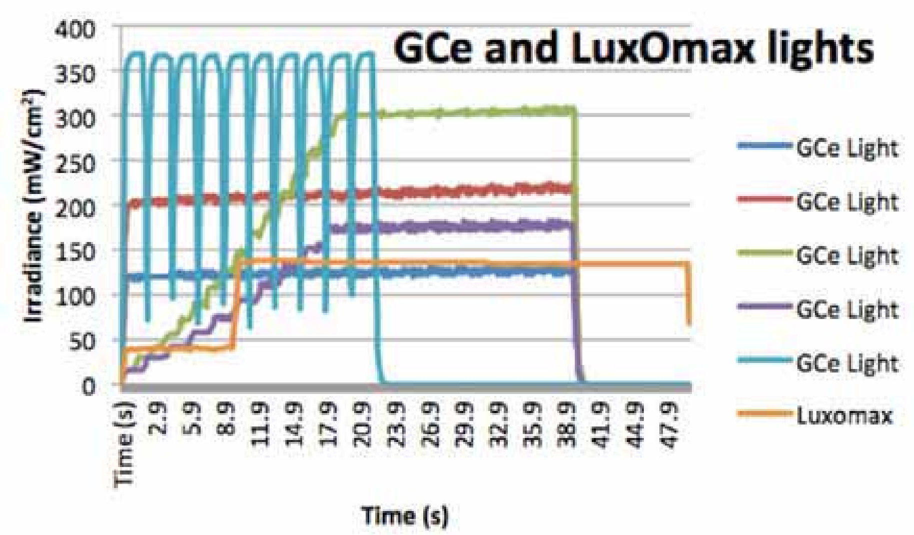

**Figure 5**. Graph showing five of the eleven output modes of the GC-e® light. A higher irradiance pulse mode, medium and low irradiance 'standard' output modes and two soft start modes of differing irradiance are displayed together with LUXoMAX® light 2 step mode for comparison.

## Second-generation LED lights (2002–2004)

LED lights have progressed rapidly over the last decade, paralleling advances in computer chip technology, with much more powerful diodes and second-generation LED units (1–2 LEDs) matching QTH units for performance. The major improvement between the first and second-generation lights was in LED 'chip' design. By incorporating miniaturized chips in second-generation units, more LEDs were permitted increasing power output (1W or 5W chips) and effective irradiance. One 5W chip provided similar flux to 10–20 5mm diameter first-generation LEDs. Nowadays, efficiency has been achieved with second-generation LED units, which entered the market in 2002. Cure depths approached those of powerful QTH units in half the radiation time of the latter.[19] Among this second generation, we find a dozen more or less well-known brands. In succession and in alphabetical order, we will refer to the Bluephase® (Ivoclar Vivadent, Enderby, Leics), Elipar®Freelight 2 (3M ESPE), MiniLED® (Satelec (UK), St Neots, Cambs) (Figure 7), Translux Power Blue® (Heraeus-Kulzer, Newbury , Berks) and a few others which may or may not remain. Unlike their predecessors, most of these LED units incorporated the same single LED: the Luxeon from Lumiled V Star (RS Components, Birmingham). A single 5W LED (in reality, composed of 4 micro-LEDs) made it possible to approach or even exceed 1000 $mW/cm^2$ irradiance. The large area chip assembly is bonded directly to a large heat sink allowing high power operation without thermal damage to the LED. These lights were small, some without a fan, and offered a simple and user-friendly menu supported by batteries with no memory effect. Finally, LED curing units were competitive with halogen lamps because, despite their slightly higher price, they were incredibly simple. The best known was the inspiration for the whole generation, the much-copied MiniLED® from Satelec (Figure 7). This was followed by the attractive and highly efficient Bluephase® from Ivoclar Vivadent (Enderby, Leics) (Figure 8), LEDemetron® 1 and 2 (Kerr, Peterborough,

**Figure 6.** GC-e® (GD Dental): first-generation gun style handpiece blue multi-diode LED LAU.

**Figure 7.** Second-generation MiniLED® (Satelec): monowave blue LED LAU.

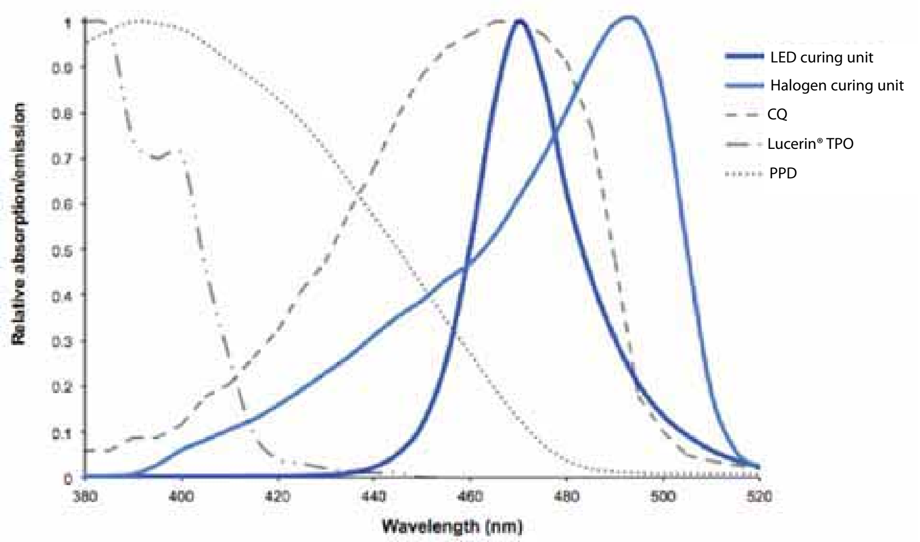

**Figure 9.** The relative spectral irradiance and absorption spectra for a conventional halogen and single-diode blue LED curing unit and three common dental photo-initiators highlighting the lack of overlap between the TPO initiatior and single-diode blue LED light-curing unit.

**Figure 8.** Second-generation Bluephase® ( Ivoclar Vivadent): monowave blue LED LAU.

Cambs), Elipar®Freelight 2 (3M ESPE) and Radii® (SDI, Dublin 9, Ireland) amongst others.

An issue which manufacturers have to address with higher power LED LAUs is how to control the heat generation problem that comes with the extra power. Cooling fans and heat-sink features were introduced to extend the life of the LEDs. Problems include automatic unit shut off due to overheating, power loss on serial continuous discharge, excessive handpiece body and/or light head heating.

## Third-generation LED lights (2004–2011)

The third generation marks the culmination of 15 years of research and 8 years of daily practice in using LED lights.[20] The advent of the third generation of curing units has represented a significant advance in the area of light-curing. It responded to the diverse needs of daily restorative and orthodontic practice, such as wide ranging power application methods, and includes units with bimodal or polywave spectra, making the units truly universal in regard to the range of materials they could cure – camphorquinone or CQ + tertiary amine, 1-phenylpropane-1,2-dione or PPD and trimethylbenzoyl-diphenyl phosphine oxide or Lucerin® TPO (Figure 9). Single spectral peak blue LED LAUs are ideal for curing CQ-amine intiated RBCs but, because CQ is bright yellow in colour and does not bleach out completely on curing, manufacturers have partly or totally replaced CQ with other paler photo-initiators capable of bleaching more fully. The problem is that these alternative initiators need near UV wavelengths to activate them effectively.

Third-generation LEDs are actually a combination of several basic LEDs, each emitting at identical, complementary or different wavelengths. Nowadays, it is this demand that defines the number, geometry and selection of the wavelengths. Just as the GC-e® light was an exception and a link in the chain between the first and second generations, the Ultra-lume 5® from Ultradent (Optident Dental Products, Ilkley, West Yorkshire) with its wide spectrum (5 LEDs in total; 1 blue and 4 violet) remains the unit that forged a path for the third generation. It was the beginning of the Polywave LED trend. It was followed in no particular order by the G-Light® and G-light Prima® (GC UK Ltd, Newport Pagnell, Bucks), Bluephase G2® and Bluephase 20i® (Ivoclar Vivadent), Valo® (Ultradent) and Smartlite®Max (Dentsply, Addlestone, Surrey). G-Light Prima and SmartLite Max are not available in the UK. Other lights have also been marketed which offer the potential to cure UV-initiated resins and composites, either by replacing the blue diode light source head with a separate UV diode head (Fusion® from Dentlight Inc, Richardson, TX 7508, USA), or by employing a wavelength adapting lens as in the Beyond® CL-628 (Beyonddent, Houston, Texas, USA) unit, claimed to be able to cure any composite with its 'dual wavelength' output. The instruction manual for the Beyond® CL-628 LED LAU states that curing wavelengths from standard output cover 420–490 nm range (for CQ-initiated RBCs) and that curing wavelengths, with the short-wavelength adapting lens in position, lie between 400–420 nm, making it compatible with PPD photo-initiators. This claim has not been confirmed/

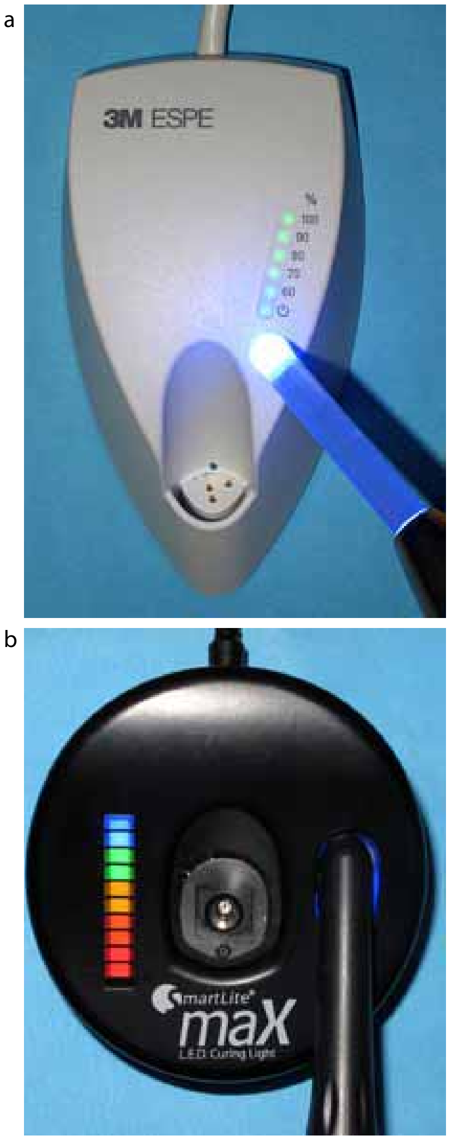

**Figure 10. (a, b)** Many third-generation units have a light meter built into the base. Elipar S10 and SmartLite maX shown.

independently verified to our knowledge.

Some concerns exist with regard to LED light curing units purchased from small manufacturers who sell their products exclusively through internet websites or via mail order from abroad and not through a dental dealership. Whilst these products are relatively inexpensive to purchase and may be marked as 'CE approved', with claims that the 'intensity' may reach a certain value, this is no quality or absolute irradiance guarantee and the unsuspecting buyer may find that the letters 'CE' actually stand for Chinese Export! The meaning of 'FDA approved', as is also stamped across pictures of adverts for dental LED LAUs featured on internet-based selling sites, is not yet clear. A malpractice claim has been upheld recently in North America in regard to premature failure of inadequately cured resin-based restorations associated with a poor light source. It was concluded that the problem could have been avoided if the light unit had been tested with a manufacturer-approved instrument, with the assistance of the practitioner's dental supply company. Caveat Emptor!

## General characteristics and technological performance of third-generation LED units

Externally, they look similar to the previous generations but, in reality, they are fundamentally different. Third-generation LED lights mark a real revolution because, as well as matching the best halogen, plasma or second-generation LED light-curing units, they offer entirely innovative clinical options. Third-generation LED lights have streamlined the basic elements common to all lights, by providing:

- A broader spectrum approaching that of QTH LAUs, but without the use of filters. Many third-generation LED LAUs incorporate violet as well as blue diodes in order to make them more universal in the range of materials they can cure.
- Irradiance ranging from 1000 mW/cm$^2$ to nearly 3000 mW/cm$^2$ with a standard tip (matching or exceeding the output of plasma arc lamps).
- A high-capacity battery with run times of about an hour or more, whilst keeping size and weight down.
- All the familiar time/power profiles.

With a fast-curing (variously called high power, turbo or plasma emulation mode) menu, at these power levels, very short exposure of 3–5 sec can be used for sealants, multi-layering techniques, bonding brackets, tacking indirect restorations or bleaching. There is also pulse-curing which allows 8–10 seconds recovery in pseudo-fast curing (as with laser polymerization). Soft-start curing menus enable enthusiasts of progressive (step; ramp; soft-start; soft energy light release or SLER; and pulse-delay) curing to use their lights for a longer period with modulated power, for example 20 seconds with only 50% of its power rating, which has the effect of not discharging the battery too quickly, even if the exposure time is longer. These modes are designed to reduce stress in the tooth and restoration, reduce heating effects and assist in maintaining marginal integrity. The soft-start polymerization concept is still valid with high power LED LAUs but stress reduction is material specific. For the first time in the history of light-curing units, several of the third-generation LED lights seem to be superior to all previous generations. Clinicians are able to adapt the irradiation mode and time to the material they are using and their restorative technique. Additionally, there are some unique functions and characteristics of this third generation.

One of the major advantages of these units was that users had access not only to fast-curing menus (3–10 seconds) but also to the pulsed menus discovered with plasma lamps and soft menus of varying profiles (15–65 seconds). Owing to their higher power, they also enabled users to return to 7–10 mm tips. Unfortunately, this also meant the return to externally vented fans for some units, bringing problems of noise and potential cross-infection risk. The third-generation Elipar® S10 from 3M ESPE offers an irradiance of 1,200 mW/cm$^2$ from a wide 10 mm tip, allowing larger restorations to be cured in 'one shot'. It is a 'monowave' or single spectral peak blue LED LCU which has been designed to be well-collimated, meaning that irradiance declines in a more gradual fashion with distance. The magnetically attachable light guides are interchangeable, allowing a 'tacking tip' option. It has a one-piece stainless steel design for robustness, and 'leak tightness'. Many less expensive units have plastic casings which may be more susceptible to fluid ingress and resisting microbial decontamination. Many LAUs in clinical practice may become contaminated, despite best efforts, and external fan-less designs with easily disinfected metal housings are preferred. The Elipar S10® has only one output mode which may be operated for 5, 10, 15 or 20 seconds or two minutes of continuous use. There is a light meter built into the base station, as is common with many third-generation units (Figure 10 a, b). Good width of cure is an important criterion for dentists wishing to irradiate large direct and indirect restorations in a single light activation.[21] Small tips cost time when curing large restorations as they demand overlapping cure cycles, and moving down from an 11 mm tip to a 6 mm tip increases the radiation time three-fold. Irradiance is usually highest in the centre of the light guide or tip face and decreases outwards. The light guide exit window or tip 'active' diameter should ideally exceed the diameter of the material to be cured by one to two millimetres. If you see fractures or stained areas at the edges of your restorations, it may be that your light guide does not overlap these areas sufficiently.

Valo® from Ultradent uses LED chips at central wavelengths of 405 nm, 445 nm and 465 nm to cure all proprietary photo-initiators. The circuitry of this Polywave third-generation unit allows standard, high power and 'plasma irradiation modes' which are stated to offer 1,000 mW/cm$^2$, 1,400 mW/cm$^2$ and 3,200 mW/cm$^2$, respectively, for 20 s, 4 s and 3 s maximum irradiation times, respectively. The convex profile of the 10 mm diameter round lens tip is placed at right angles to the wand body allowing good access (Figure 11). It replaces the flat oval 11 x 7 mm exit window design of its predecessor Ultralume 5 (Optident Dental Products, Ilkley, West Yorks) (Figure 11a). As Valo's light source head cannot be removed for autoclaving, barrier protection is mandatory (Figure 11b).

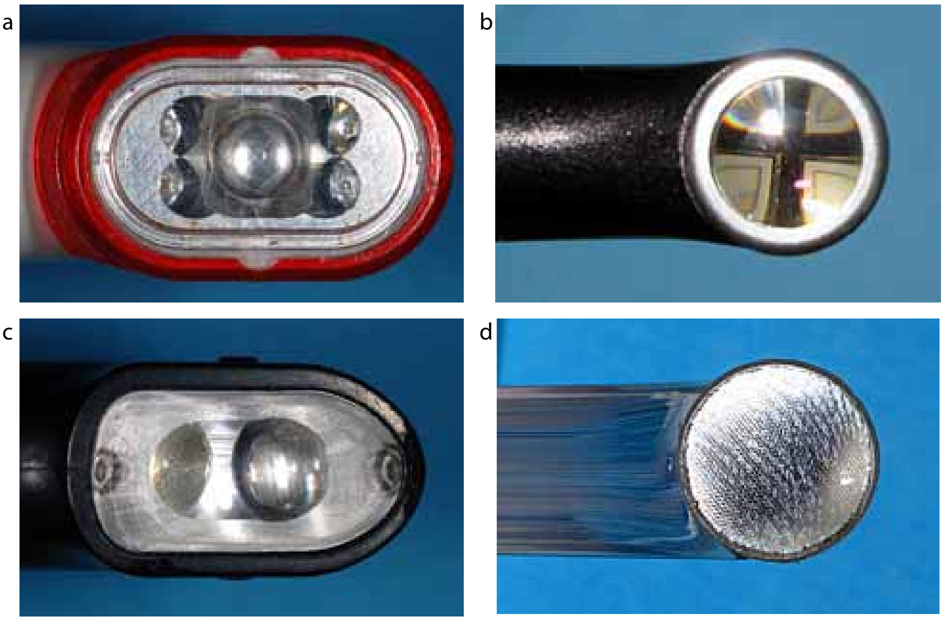

**Figure 11.** Light source exit windows or tips for four wand style third-generation lights. **(a)** Ultralume 5, **(b)** Valo (Ultradent), **(c)** SmartLite maX (Dentsply, and **(d)** Elipar S10 (3M ESPE).

## Power

Power has risen significantly, resulting in irradiance levels going from 1,000 plus up to nearly 6,000 mW/cm$^2$ for one particular unit (Flashmax2® and PS®; CMS Dental, DK-1408, Copenhagen K, Denmark) with other units like Valo® (Ultradent) claiming in excess of 3,000 mW/cm$^2$ in plasma emulation mode and Satelec Supercharged® (Satelec (UK) Ltd, St Neots, Cambs) delivering similar irradiance from a 5.5 mm diameter tip. There is no indication that manufacturers have reached the upper limit for irradiance yet!

With the exception of Flashmax2® and PS®, which only operate at maximum power for 1 or 3 s, other units can be programmed for low, standard and high power settings, allowing different combinations of radiant exposure (the product of irradiance and time and expressed as J/cm$^2$) and cure rates, allowing the dentist good control over irradiance for diverse clinical applications. Thus we have lights that are capable of curing orthodontic cements quickly at high power levels, ensuring fast and precise bracket positioning. However, the trend towards ever higher irradiances, coupled with extremely short radiation times, has been based on the assumption that there is a universal reciprocal relationship between irradiance and irradiation time, otherwise known as the total energy concept.[22]

The kinetics of polymerization is complex and theoretical considerations indicate that any simple reciprocity does not exist as degree of cure depends on the product of exposure duration raised to power one and irradiance to the power 0.5–0.6. The universality of the total energy concept has been discredited by subsequent studies[23–26] and sometimes longer exposure durations at lower irradiance lead to higher conversion at matching radiant exposures.[24,26] There is a maximum cure rate possible and doubling irradiance may only reduce cure time by one third whilst maintaining conversion. Above a certain irradiation level, cure rate is not improved. Composite resins have a finite photon absorption rate and a greater radiant exposure is required to produce equivalent conversion with very high irradiances and short radiation times, because irradiance dependent de-activation mechanisms have to be accounted for. The effect and its possible consequences are complex and difficult to measure with our viscous dental composites. Also, given that there is a high degree of inefficiency of light into and through aesthetic biomaterials for the purposes of photoactivation,[27] very high irradiances may increase the risks of acute and cumulative effects on the eyes of dental personnel from back reflected blue light.[28]

Problems remained for manufacturers as market demands drove them to producing ever higher irradiance units. Heat-sink features and automatic thermal cut-outs (Elipar® S10 – Figure 11d; Satelec Supercharged®), cooling fans (Bluephase 20i®; Demi® and Demi Plus® from Kerr), pulsed light output (Radii Plus® from SDI), periodic level shifting (Demi and Demi Plus) programmes were all developed to combat LED overheating during continuous use, leading to declining irradiance and possible spectral shifts, as well as temporary or permanent diode failure. By adding ever more powerful chips of varying wavelengths to produce powerful broad spectrum or polywave LED LAU, new issues arose for manufacturers and researchers to address. As well as offering energy stability over time (stable irradiance), spectral stability is even more critical for LED LAUs than their QTH predecessors as a small variation in emission bandwidth can correspond to a withdrawl from the absorption peak of the photo-initiator.[28]

Independently assessed irradiance values may not coincide with manufacturers' values and Perez *et al* have reported discrepancies of up to 280% in magnitude.[29] This is a serious issue when the quantity of energy that the device produces in a set time

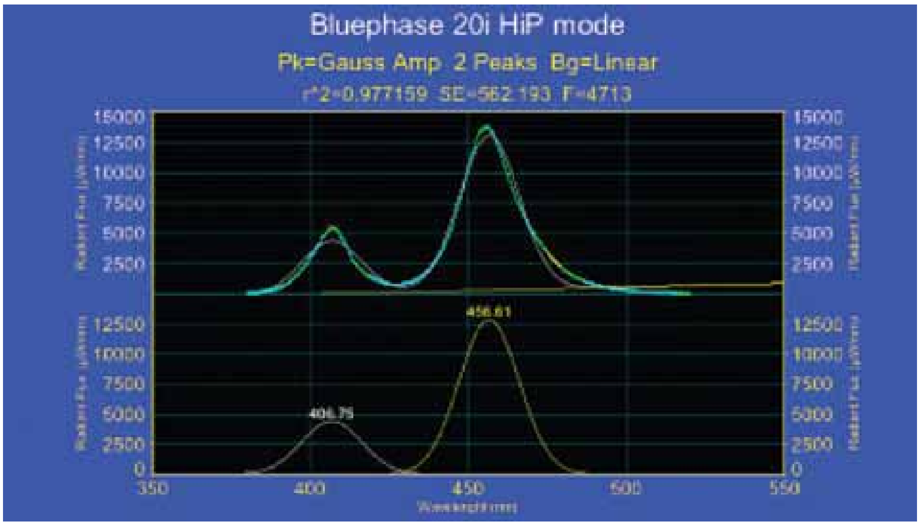

**Figure 12.** Deconvoluted spectrum for Bluephase 20i® (Ivoclar Vivadent) third-generation LED LCU tested in high power mode revealing two (bimodal) spectral wavelength peaks.

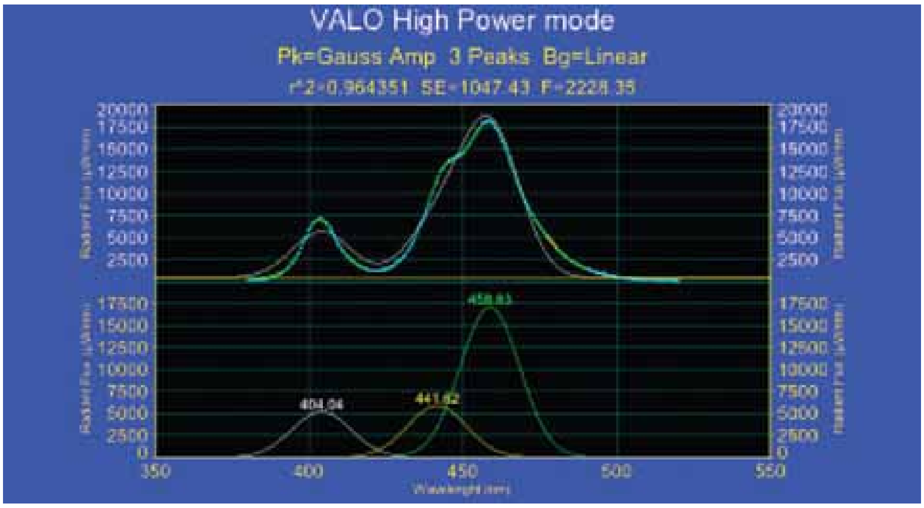

**Figure 13.** Deconvoluted spectrum  for Valo third-generation Polywave LED LCU tested in high power mode revealing three distinct spectral peaks from its diode package.

is far greater or less than the dentist believes to be the case, having practical and biological implications. In addition, operating multiple chips or LEDs simultaneously to achieve high irradiance may lead to irradiance instability. Perez *et al* reported that the second-generation LEDemetron, with four LEDs, and the Ultralume 5, with its combination of four violet and one blue LED, exhibited poor energy stability (irradiance declines over run time) relative to units which only had one or two LEDs operating simultaneously.[29] Poor energy stability can be associated with LCUs that have multiple high power LEDs operating simultaneously. It is debatable whether units with irradiance values above 1,500 mW/cm$^2$ or 2,000 mW/cm$^2$ are necessary for routine curing procedures, unless the operator is trying to light cure through thick ceramic or indirect resin restorations, or needs ultra-fast curing for orthodontic bonding applications. The situation may change in the future if resin-based restoratives can be modified to allow them to be properly polymerized to 2 mm thickness or more with very short radiation times of 5 seconds or less. The jury is still out on this issue!

## Spectrum

The spectrum can extend over all wavelengths. In dentistry, a third-generation LED light will often emit according to different spectra. Therefore, it is important to be aware of the figures for the relative outputs at different wavelengths from the figures publicized, as whether or not certain composites or bonding agents can be cured will depend on these values.[21,30–33] It is frequently assumed, incorrectly, that blue LED LCUs will only polymerize CQ-initiated resins effectively, whereas QTH LAUs, because of their broader spectral coverage, are required for PPD or TPO initiated RBCs. However, the manufacturers of some blue LED units have cleverly chosen to modify their emission spectra in order to polymerize more light-sensitive products. Brandt *et al* have reported the effect of different photo-initiators and LAUs on degree of conversion (DC) of experimental RBC formulations.[34] One QTH and two LED LAUs were tested with CQ, PPD or CQ/PPD initiated RBCs of matching resin and filler formulations. The photo-activation time of the lower irradiance LED LAU (Ultrablue IS) ~600 mW/cm$^2$ and the higher irradiance QTH LCU (XL 2500) ~900 mW/cm$^2$ were adjusted to ensure that all samples received the same radiant exposure. The emission peaks for these two LAUs were 456 nm (Ultrablue IS) and 484 nm (XL 2500). When XL 2500 was used, RBCs formulated with CQ presented higher DC than those with CQ or CQ/PPD, which did not differ between them. With UltraBlue IS there was no significant difference in DC with any of the three photo-initiator systems. Because UltraBlue IS's light emission peak was shifted to 456 nm, it presented a good overlap with PPD. Spectral analysis showed that only 50.5% of the light energy emitted from XL 2500 QTH LAU was below 470 nm (the area where PPD absorbs more light), whereas for the UltraBlue IS unit, 78.1% of the energy was emitted at wavelengths below 470 nm. Thus spectral analysis was able to explain the conversion data for the different RBCs. The way in which this spectrum is selected also varies. For instance, some manufacturers prefer the power associated with a narrow wavelength range (450–470 nm), whereas others prefer to choose a more multi-purpose 'Polywave' spectrum (G-Light, the 2009 Bluephase range of LCUs, Valo, SmartLite Max and now Scanwave by MiniLed$^{TM}$), while possibly reducing the power over a specific wavelength that does not match their own composites. Figures 12 and 13 show deconvoluted spectra from Bluephase 20i (2 diode wavelengths) and Valo (3 diode wavelengths) Polywave third-generation Polywave LED LCUs demonstrating the different diode wavelengths. Note the broader wavelength range encompassed by these Polywave units. What is certain nowadays is that the recent arrival of UV diodes makes all things possible: the entire spectrum is now covered by these powerful LEDs, ranging from 400 nm to 480 nm and higher.

**Acknowledgments**

The authors acknowledge the advances made to the development of light curing technology in dentistry by dental manufacturers and research workers. Their contributions will significantly benefit patient care.

**Disclaimer**

The authors confirm that they have no financial interest in any of the products mentioned in these articles and have only been reimbursed expenses for test evaluation purposes concerning a prototype of the Scanwave™ (Acteon) light activation unit.

## References

1. Young KC, Hussey M, Gillespie FC, Stephen KW. The performance of ultraviolet lights used to polymerize fissure sealants. *J Oral Rehab* 1977; **4**: 181–191.
2. Ruyter IE, Oysaed H. Conversion in different depths of ultraviolet and visible light activated composite materials. *Acta Odontol Scand* 1982; **40**: 179–92.
3. de Lange C, Bausch JR, Davidson CL. The curing pattern of photo-initiated dental composites. *J Oral Rehab* 1980; **7**: 369–375.
4. Shortall AC, Harrington E. Effect of light intensity on polymerisation of three composite resins. *Eur J Prosthodont Rest Dent* 1996; **4**: 71–76.
5. Barghi N, Fischer De, Pham T. Revisiting the intensity output of curing lights in private dental offices. *Compend Contin Dent Educ* 2007; **28**: 380–384.
6. 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**: 105–108.
7. Shortall A, Harrington E. Guidelines for the selection, use and maintenance of visible light activation units. *Br Dent J* 1996; **180**(10): 383–387.
8. Shortall AC, Harrington E. Effectiveness of battery powered light activation units. *Br Dent J* 1997; **183**(3): 95–100.
9. Rueggeberg FA. State-of-the-art: dental photocuring – a review. *Dent Mater* 2011; **27**: 39–52.
10. Price RB, Labrie D, Kamzi S, Fahey J, Felix CM. Intra- and inter-brand accuracy of dental radiometers. *Clin Oral Invest* 2011; May 12 [Epub ahead of print].
11. Shortall AC, Harrington E, Wilson HJ. Light curing unit effectiveness assessed by dental radiometers. *J Dentistry* 1995; **23**: 227–232.
12. Round HJ. A note on carborundum. *Electricity World* 1907; **19**: 309.
13. Mills RW, Uhl A, Jandt KD. Optical power outputs, spectra and dental composite depths of cure, obtained with blue light emitting (LED) and halogen light curing units. *Br Dent J* 2002; **193**(8): 459–463.
14. Kennedy J. Portable LED photocuring device. In: United States Patent. vol. 5.420.768. USA, 1993.
15. Mills RW. Blue light emitting diodes – another method of light curing? *Br Dent J* 1995; **178**: 169.
16. Fujibayashi K, Ishimaru K, Kohno A. A study on light activation units using blue-light emitting diodes. *J Jap Dent Pres Acad* 1996; **39**: 180–188.
17. Whitters CJ, Girkin GM, Carey JJ. Curing of dental composites by use of InGaN light-emitting diodes. *Optics Letters* 1999; **24**(1): 67–68.
18. Mills RW, Jandt KD, Ashworth SH. Dental composite depth of cure with halogen and blue light emitting diode technology. *Br Dent J* 1999; **186**(8): 388–391.
19. Shortall AC. How light source and product shade influence cure depth for a contemporary composite. *J Oral Rehab* 2005; **32**: 906–911.
20. Pelissier B, Chazel JC, Duret F. Les Lampes à LED de troisième génération. *Alpha Oméga News* 2007; **109**(5): 12–15.
21. Palin WM, Senilmaz DP, Marquis PM, Shortall AC. Cure width potential for MOD resin composite molar restorations. *Dent Mater* 2008; **24**: 1083–1094.
22. Halvorson RH, Erikson RL, Davidson CL. Energy dependent polymerization of resin-based composites. *Dent Mater* 2002; **18:** 463–469.
23. Musanje L, Darvell BW. Polymerization of resin composite restorative materials: exposure reciprocity. *Dent Mater* 2003; **19**: 531–541.
24. Peutzfeldt A, Asmussen E. Resin composite properties and energy density of light cure. *J Dent Res* 2005; **84**: 659–662.
25. Leprince JG, Hadis M, Shortall AC, Ferracane JL, Devaux J, Leloup G, Palin WM. Photoinitiator type and applicability of exposure reciprocity law infilled and unfilled photoactive resins. *Dent Mater* 2011; **27**: 157–164.
26. Hadis M, Leprince JG, Shortall AC, Deveaux J, Leloup G, Palin WM. High irradiance curing and anomalies of exposure reciprocity law in resin-based materials. *J Dentistry* 2011; **39**: 549–557.
27. Watts DC, Cash AJ. Analysis of optical transmission by 400–500 nm visible light into aesthetic dental biomaterials. *J Dentistry* 1994; **22**: 112–117.
28. Bruzell Roll EM, Jacobsen N, Hensten-Pettersen A. Health hazards associated with curing light in the dental clinic. *Clin Oral Invest* 2004; **8**: 113–117.
29. del Mar Pérez, M, Pérez-Ocón F, Lucena-Martín C, Pulgar R. Stability and reproducibility of radiometric properties of light curing units (LCUs). Part II: LED LCUs. *Dent Mater J* 2008; **27**: 292–299.
30. Uhl A, Mills RW, Jandt KD. Photoinitiator dependent composite depth of cure and Knoop hardness with halogen and LED light curing units. *Biomaterials* 2003; **24**: 1787–1795.
31. Price RB, Felix CA, Andreou P. Effects of resin composite composition and irradiation distance on the performance of curing lights. *Biomaterials* 2004; **25**(18): 4465–4477.
32. Ogunyinka A, Palin WM, Shortall AC, Marquis PM. Photoinitiation chemistry affects light transmission and degree of conversion of curing experimental dental resin composites. *Dent Mater* 2007; **23**: 807–813.
33. Price RB, Fahey J, Felix CM. Knoop hardness of five composites cured with single-peak and polywave LED curing units. *Quintessence Int* 2010; **41**: e181–e191.
34. Brandt WC, Schneider FJ, Frollini E, Correr-Sobrinho L, Sinhoreti MA. Effect of different photo-initiators and light curing units on degree of conversion of composites. *Braz Oral Res* 2010: **24**: 263–270.