The method of polymerization of resin-based composites (RBCs) determines the technique of insertion, direction of polymerization shrinkage, finishing procedure, color stability, and amount of internal porosity. Initially, RBCs were chemically activated and supplied as two pastes containing a benzoyl peroxide initiator and an aromatic tertiary amine activator (N, N-dimethyl-p-toluidine). They were bulk-filled with the direction of polymerization shrinkage toward the center of the mass, had internal pores that inhibited polymerization during curing, provided no control with the working time, increased the finishing time, and had less color stability due to breakdown of tertiary amines. Then, light-activated systems were introduced, which used ultraviolet (UV) light. Because these methods had the harmful biologic effects of UV rays and poor penetration through the tooth structure, they were replaced by visible blue light-activated systems. These commonly employ camphorquinone (CQ) as the photoinitiator (474 nm) and an aliphatic amine activator (dimethylaminoethyl methacrylate). They are filled incrementally with the polymerization shrinkage directed toward the light source. They have better depth of cure with a controllable working time, no internal porosity, enhanced color stability due to aliphatic amine, more translucency, and improved esthetics. One of the major disadvantages of light-cured RBCs is polymerization shrinkage and associated stress generation that may lead to clinical failure of RBC restorations. Light-cured RBCs generate higher polymerization stresses as compared with chemical-cured RBCs. The type of curing light and curing mode partly governs and influences

Learning Objectives
After reading this article, the reader should be able to:

- summarize the evolution of light-curing units for resin-based composites.
- discuss the advantages and disadvantages of various light-curing devices.
- explain various light-curing modes.

Abstract: There has been a continual advent of improved technologies in dentistry. Among these are the material sciences of resin-based composites (RBCs). Since the introduction of light-cured RBCs, the problem of polymerization shrinkage and the methods used to overcome this have concerned clinicians and researchers. Types of curing light and modes of curing have been shown to affect the degree of polymerization and related shrinkage of RBCs. This review, which is divided into two parts, discusses the contemporary light-curing units. Part I explores the evolution in light-curing units and different curing modes. Part II highlights the clinical considerations regarding light curing of RBCs that are important for achieving optimal curing and maximum polymerization of RBCs in a clinical setting.
the quantity and quality of RBC polymerization. Another way to improve the degree of polymerization and reduce the shrinkage stresses is by the use of extra-oral curing with pressure and vacuuming. In Part 1, the authors explain the different light-curing units, operating characteristics, and curing modes for RBCs. The associated clinical considerations and factors influencing the efficiency of light-curing units are discussed in the second part of the review.

LIGHT-CURING UNITS
Various light-curing units belonging to different generations are available commercially. Usually, they are hand-held devices with a light source and light guide of fused optical fibers. A curing unit with a minimal light output of 550 lux is considered appropriate for dental use.

Quartz Tungsten Halogen (QTH)
Quartz tungsten halogen (QTH) devices are the most widely used light-curing units and contain a quartz bulb with a tungsten filament in a halogen environment. The units irradiate both UV and white light that must be filtered to remove heat and transmit light only in the violet-blue region of the spectrum that matches the photoabsorption range of CQ. They are available in continuous, step-cure, or ramp-cure modes. Less than 0.5% of the total light produced in a QTH is suitable for curing, and most is converted to heat. To minimize heating, UV and infrared band-pass filters are inserted just before the fiber optic system is used. Orange filters are widely used because they are complementary to blue and absorb blue radiation. A small fan is employed to dissipate unwanted heat from the filters and reflector. Usually, filters degrade with time due to the heating and cooling cycles. QTH-curing lights work at wavelengths of 400 nm to 500 nm with output ranging from 400 mW/cm² to 800 mW/cm². QTH-curing lights have been shown to produce the smallest amount of residual monomer in RBCs. They have a slower cure time (about 15 sec to 20 sec). The units are relatively large and cumbersome. The lights (bulbs) decrease in output with time and thus need frequent replacement. They have low-energy performance and generate high temperatures. They require a filter and ventilating fan.

Turbo tips provide greater curing intensity and faster curing than QTH units; they become smaller as they exit the curing light. More recently, enhanced halogen curing lights have been introduced commercially. To date, mixed data have been reported from in vitro studies regarding the performance of these light-curing units. Hardness of RBC specimens (2 mm) obtained following curing with some of these high-intensity lights is found to be similar to conventional QTH- and LED-curing lights. However, other units have shown greater polymerization shrinkage and less effective curing of RBC than with conventional QTH units. Thus, further research is required to identify their potential in dental practices.

Light-Emitting Diode
Light-emitting diode (LED) lamps are based on LEDs. Initially, low-power blue LEDs using silicon carbide (first-generation LEDs) having a power output of 7 μW per LED were introduced. Blue LEDs, or second-generation LEDs, were built on gallium nitride technology and had a power output of 3 mW (400-fold increase). The second generation LEDs are considered to be more effective in curing composites than their predecessors. These units are cordless, small, lightweight, and battery-powered. They do not require filters because they emit light at a specific wavelength within the 400-nm to 500-nm photoabsorption range of CQ. Thus, all the emitted light is useful, resulting in high-energy performance of the curing light. The spectral output falls between 410 nm and 490 nm or between 450 nm and 490 nm. These units show a constant effectiveness without any drop in intensity with time because the diodes do not require frequent replacement. Because no heat generation occurs during curing, a cooling fan is not needed.
Disadvantages:
- The batteries must be recharged.
- They cost more than conventional halogen lights.
- The curing time is slower than that of plasma-arc curing lights and some enhanced halogen lights.

A literature review suggests LED devices and conventional QTH-curing lights have no significant differences. LED units are considered similar or better compared with QTH units regarding the degree of polymerization, microleakage at enamel and dentin margins, wear rate of RBCs, flexural properties of cured RBCs, and hardness of cured RBCs. Also, bond strength values for dual-cure resin cements used in cementation of indirect RBC restorations is found to be equivalent for LED- and QTH-curing lights. However, depth of curing with LED units is higher than QTH devices, and QTH-curing lights tend to show more yellowing of RBCs than LEDs. The variables of water sorption and solubility of RBCs are not dependent on the type of curing light used.

Few authors consider conventional QTH-curing lights to be better than LEDs. LEDs have been shown to take longer for complete curing of microfilled and hybrid RBCs and do not satisfy manufacturers’ claims for minimum intensities. Thus, a necessary increase in the light intensity of these units has been suggested. Future LEDs will need a high power output to compensate for a narrow bandwidth or broader frequency spectrum. Thus, the newer generation units of LEDs are a good option as curing-light devices for RBCs but need further improvements.

Plasma Arc
Plasma-arc curing (PAC) lights are high-intensity light-curing units. They have more intense light sources (fluorescent bulb-containing plasma), allowing for shorter exposure times. Light is obtained from an electrically conductive gas (xenon) called plasma that forms between two tungsten electrodes under pressure. The light spectrum provided by plasma is limited. The wavelength of high-intensity light emitted is determined by the bulb-coating material and filtered out to minimize transmission of infrared and UV energy and to allow emission of blue light (400 nm to 500 nm). This also helps remove the heat from the system. Because a high-intensity light is available at lower wavelengths, these units are able to cure composites with photoinitiators other than camphorquinone. The comparative clinical efficiency of PAC lights largely depends on the type of photoinitiator used. These units have a high energy output and short curing time. An exposure of 10 secs from a PAC light is equivalent to 40 secs from a QTH light. These units have been shown to have higher conversion rates and depths of cure for RBCs as compared with QTH units. These systems work at wavelengths between 370 nm and 450 nm or between 430 nm and 500 nm.

Disadvantages:
- The heat production must be controlled.
- They are expensive.
- The lamp (bulb) replacement is costly.
- Most devices are large, heavy, and bulky.
- They have low-energy performance.
- Filters and ventilating fan are required.

The results obtained from the QTH units are better than those acquired from PAC units. RBCs cured with a PAC unit have shown more polymerization shrinkage than with QTH units. Despite rapid curing, a xenon lamp produces marginal contraction with dentin bonding agents. The hardness values of RBC specimens cured by the PAC units have been shown to be significantly lower than LED and QTH units. The recommended time of 3 secs for PAC units is inadequate and should be doubled to obtain optimal mechanical properties of RBCs. An incremental technique of 2 mm should be followed. These units, when used in combination with QTH units, have been shown to provide higher bond strength values for dentin bonding agents. The devices are best suited for cementation of orthodontic bands and brackets.

Argon Laser
Laser lamps are high-intensity lamps based on the laser principle. The emitted wavelength depends on the material used (argon produces blue light). Argon laser lamps have the highest intensity. These lamps work within a limited range of wavelengths, do not require filters, and require shorter exposure times for curing RBCs. The devices generate little infrared output, so not much heat is produced. They work at specific bandwidths of light in the ranges of 454 nm to 466 nm, 472 nm to 497 nm, and 514 nm. Because a laser is a narrow beam of coherent light, no loss of power over distance occurs as in seen in QTH units. Therefore, argon laser curing lights are the units of choice for inaccessible areas.

Disadvantages:
- The curing depth is limited to 1.5 mm to 2 mm.
- The curing tip is small, so more time is needed to cure the RBCs.
- They have narrow spectral outputs.
- They are expensive.
Studies have reported similar results for both laser and QTH units. No difference in bond strength is seen between the argon laser and standard QTH units. Laser devices have been shown to produce an increased degree and depth of cure for RBCs. The laser systems have also demonstrated greater material wear, more polymerization shrinkage, and increased marginal leakage. Recently, a diode-pumped solid-state (DPSS) laser (473 nm) was introduced, and its effect on the degree of RBC polymerization has been tested. One study demonstrated these units produce better or similar polymerization and color change than QTH and LED devices do and possess high potential to be an alternative to the other light-curing systems. These devices are not available commercially. Thus, these laser-based units are promising as curing lights for RBCs; their usage is still not a widely accepted idea in clinical settings.

USE OF RADIOMETERS
The light intensity and output of a light-curing unit can be monitored using a portable or built-in radiometer chairside. A radiometer measures the number of photons, unit area, and unit time through a standard 11-mm diameter window. Curing unit tips that are smaller or larger cannot be tested effectively. Usually, a minimal output higher than 300 mW/cm² is recommended. Also, the radiometer measures all light energies and cannot discriminate the light energy of the photoinitiator, limiting the measurement of the real value.

LIGHT-CURING TECHNIQUES
Soft Start
One method to reduce polymerization shrinkage-associated stresses and microleakage is by providing an initial low rate of polymerization. This may reduce the stress buildup by supplying extended time for stress relaxation before reaching the gel phase. This can be accomplished by using a soft-start curing technique in which the curing begins with a low intensity and finishes with a high intensity. This causes the maximal possible conversion to occur only after much of the stress has been relieved. Various light-curing units automatically provide one or more soft-start exposure sequences. Some produce a 100 mW/cm² output for 10 secs, followed by an immediate increase to 600 mW/cm² output for 30 secs. Soft-start polymerization is divided into three techniques: stepped, ramped, and pulse-delay. (Figure 1).

Ramped
During exposure, intensity is gradually increased or "ramped up." This can be in stepwise, linear, or exponential modes. For ramped curing, the intensity is increased with time (30 secs) either by bringing the light toward the tooth from a distance, curing through a cusp, or using a curing light designed to increase in intensity. This sequential curing of composite from low to high intensity significantly reduced polymerization shrinkage without compromising the depth of cure. Ramp curing allows the light-cured material to have a longer gel phase in which polymerization contraction stresses are dissipated more readily.

Staged (Delayed Curing)
In this format, the restoration is initially cured at low intensity to contour and shape the restoration in occlusion, followed by a second exposure to completely cure the restoration. This allows substantial relaxation of polymerization stresses. The longer the period available for relaxation, the lower the generation of residual stresses is. This method also aids in the finishing of composite restorations—a partially cured composite material can be easily finished as compared with fully cured material. By filtering the light during an initial cure, obtaining a soft, easily finished material is possible. Thereafter, the filter is removed and the composite is cured completely.

Pulse Delay
In the pulse-delay method, a series of exposure pulses is used, each separated by a dark interval. An initial exposure of up to 1 J/cm² is considered to be most efficient in reducing shrinkage stresses. Another important parameter is delay time between irradiances. During the dark period, polymerization reaction occurs at a reduced rate. Thus, longer delays lead to a greater amount of chain relaxation. Significant reductions in shrinkage stress and microleakage and increased microhardness have been reported for pulse-delay methods, with dark periods from 1 min to 5 mins. For pulse-delay curing, the greatest reduction of polymerization shrinkage is achieved with a delay of 3 mins to 5 mins. No statistically significant difference is reported in microleakage of nanofilled and microhybrid RBCs cured with different soft-start polymerization modes (pulse, ramp, and staged).

High Intensity
High-intensity curing allows for shorter exposure times for a given depth of cure. A depth of 2 mm can be cured in 10 secs
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with a PAC light and 5 secs with an argon laser-curing light, as compared with 40 secs by a QTH lamp. A high-intensity curing initiates a multitude of growth centers during an initial irradiation period along with a final polymer with higher cross-link density. Because the relationship between energy density and post-gel shrinkage strain is considered to be linear, high-energy densities may translate into increased stress levels but do not result necessarily in high degrees of conversion or superior mechanical properties. Therefore, although high-intensity curing may lead to the same conversion rate, degree of polymerization shrinkage, and mechanical properties, it likely leads to greater shrinkage stresses.

Disadvantages:
- Short exposure times cause accelerated rates of curing and insufficient time for stress relaxation. This leads to greater shrinkage stresses and a poorer interface.
- High-intensity light curing has a narrowed wavelength range for the output. Therefore, the wavelength range of the light source must be coincident with the photoinitiator.
- Heat is a significant problem.
- It may not produce the same type of polymer network during curing.
- Using a higher intensity of light for shorter exposure time is reported to result in more cytotoxicity than a longer curing time with lower intensity.

Extra-Oral Curing

Usually, extra-oral curing is used for the fabrication of indirect RBC restorations (inlays, veneers, metal-free bridges, etc) that are processed in the laboratory. These laboratory photocuring units (LPUs) work with various combinations of light, heat, pressure, and vacuum to increase the degree of polymerization and wear resistance of RBCs. Hardness and depth of cure of an indirect RBC can be influenced by the LPUs employed. It is reported that LPUs, which provide light curing in conjunction with heat and nitrogen pressure, result in a significant increase in hardness and tensile strength of RBCs.

BIOLOGICAL SAFETY OF LIGHT-CURING UNITS

Various high-intensity light sources have been developed to polymerize RBCs more rapidly. Since their introduction, any associated adverse biologic effect of these units has concerned clinicians and led to the evaluation of the biologic safety of the high-intensity blue light units and sources. Wataha et al observed that when human monocytic cells were irradiated with three light sources (QTH, plasma arc, and laser), the secretion of TNF-α was not induced following exposure. Thus, exposure to blue light cannot be considered a possible inflammatory risk factor in dental tissues during curing of composites. A reduction in toxicity associated with a RBC is also possible if the curing mode is adapted to the type of RBC used. It has been suggested additional cytotoxicity tests in animal models are needed before confirmation of the clinical risks can be made.

Another concern is the electromagnetic interference with cardiac pacemakers during the operation of contemporary electrical dental equipment, including light-curing units. Although initial reports have shown no deleterious effects of these composite curing lights on the rate or rhythm of cardiac pacemakers or implantable cardioverter-defibrillators, more recent literature indicates that the battery-operated composite curing light may produce problems in certain patients.

CONCLUSION

Polymerization shrinkage is the main disadvantage of RBCs. Both curing lights and curing methods contribute greatly to this shrinkage. The clinical performance of the new generation of light-curing units is reported to be similar to the conventional units. These new generation systems have high power density, high light intensity, and shortened exposure time, leading to reduced chairside time and enhanced depth of cure. However, these high-intensity units have disadvantages and are not readily used in dental practice. Further modification and improvement of the light units may help achieve the best outcome and successful RBC restorations. Similarly, curing techniques, such as soft-start...
polymerization kinetics of RBCs. Thus, both the quantity and quality of polymerization can be improved with a proper selection of light-curing units and clinical curing techniques.

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Light-Curing Considerations for Resin-Based Composite Materials: A Review. Part I

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This article provides 2 hours of CE credit from AEGIS Publications, LLC. Record your answers on the enclosed answer sheet or submit them on a separate sheet of paper. You may also phone your answers in to (215) 504-1275 or fax them to (215) 504-1502 or log on to www.compendiumlive.com and click on “Continuing Education.” Be sure to include your name, address, telephone number, and last 4 digits of your Social Security number.

1. A curing unit with a minimal light output of how many lux is considered appropriate for dental use?
   a. 350
   b. 450
   c. 550
   d. 650

2. QTH devices are the most widely used light-curing units and contain:
   a. a quartz bulb.
   b. a tungsten filament.
   c. a halogen environment.
   d. all of the above

3. Less than 0.5% of the total light produced in a QTH is suitable for curing, and most is:
   a. converted to heat.
   b. the wrong wavelength.
   c. the wrong frequency.
   d. the wrong amplitude.

4. Blue LEDs, or second-generation LEDs, were built on which technology?
   a. silicon carbide
   b. gallium nitride
   c. selenium fluoride
   d. tungsten halide

5. The comparative clinical efficiency of plasma-arc curing lights units largely depends on the:
   a. type of photoinitiator used.
   b. distance between the source and composite.
   c. type of transmission line used.
   d. availability of a high-voltage electrical commercial power source.

6. Argon laser curing lights are the units of choice for:
   a. inaccessible areas.
   b. anterior restorations.
   c. underneath metal crowns.
   d. composites that use seventh-generation bonding techniques.

7. A radiometer measures the number of photons, unit area, and unit time:
   a. by measuring reflected light in a sensor.
   b. through a standard 11-mm diameter window.
   c. only in dark ambient light conditions.
   d. using a relativity-based algorithm.

8. For ramped curing, the intensity is increased with time (30 secs) by:
   a. bringing the light toward the tooth from a distance.
   b. curing through a cusp.
   c. using a curing light designed to increase in intensity.
   d. all of the above

9. For pulse-delay curing, the greatest reduction of polymerization shrinkage is achieved with a delay of:
   a. 3 to 5 secs.
   b. 3 to 5 mins.
   c. 3 to 5 hours.
   d. 3 to 5 days.

10. Usually, extra-oral curing is used for the fabrication of indirect RBC restorations (inlays, veneers, metal-free bridges, etc) that are:
    a. used in patients with excessive saliva.
    b. in need of an immediate repair to a composite.
    c. processed in the laboratory.
    d. extremely shade-sensitive for esthetic situations.