REVIEWS

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Photopolymerization of Dental Composites – Light Source and Light Intensity Dependent Technique

Fotopolimeryzacja materiałów złożonych – technika zależna od źródła światła i jego natężenia

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A – concept; **B** – data collection; **C** – statistics; **D** – data interpretation; **E** – writing/editing the text;
F – compiling the bibliography

Abstract

The paper reviews the current literature concerning the available light sources used for dental composite polymerization. Among the available curing devices the most popular are halogen lamps, plasma lamps, diode based lamps (LED) and argon lasers. Each of these groups is characterized by distinct quality of light, which determines the correct course of curing of composite materials. The paper discusses advantages and disadvantages of devices representing all groups of lamps (**Dent. Med. Probl. 2013, 50, 1, 71–77**).

Key words: photopolymerization, light-cured composites, halogen, plasma, LED, argon curing light.

Streszczenie

Proces utwardzania światłem zrewolucjonizował stomatologię w sensie praktycznym i naukowym. Z wyjątkiem procedury łączenia, prawdopodobnie nie istnieje żadna inna procedura, która sprzyjałaby coraz łatwiejszemu, wydajniejszemu i bardziej produktywnemu działaniu z zakresu stomatologii praktycznej. Jak większość znaczących osiągnięć w tej dziedzinie, stale udoskonalana technika stosowania procedury utwardzania światłem w stomatologii była rezultatem nowatorskich zastosowań wdrażanych do procesu leczenia klinicznego. W pracy na podstawie piśmiennictwa przedstawiono informacje o podstawowych źródłach światła stosowanych w stomatologii do polimeryzacji materiałów złożonych. Opierając się na badaniach nad kinetyką skurczu polimeryzacyjnego lampą, stosowano lampy polimeryzacyjne, które należy podzielić na 4 grupy – lampy halogenowe, ksenonowe, półprzewodnikowe i lasery argonowe. Każda z tych grup ma charakterystyczne właściwości dotyczące jakości emitowanego światła, warunkujące poprawny przebieg utwardzania materiału złożonego. Skuteczność polimeryzacji zachodzącej w materiale światłoutwardzalnym zależy m.in. od częstotliwości i intensywności użytego światła. Największy procent spolimeryzowanych cząsteczek monomeru powstaje przy długości światła 450–490 nm, osiągając maksimum pracy przy 468 nm. W artykule opisano zalety i wady urządzeń reprezentujących wymienione grupy (**Dent. Med. Probl. 2013, 50, 1, 71–77**).

Słowa kluczowe: proces fotopolimeryzacji, światłoutwardzalne materiały złożone, lampy halogenowe, plazmowe, diodowe, argonowe.

With the development of new dental techniques, we observe increasing use of dental composite materials which are cured with light-emitting polymerizing devices.

To initiate the curing reaction of composite materials a photoinitiator and energy of radiation from the blue range of visible light are necessary. The light must be of a certain wavelength (frequency). The effectiveness of polymerization differs depending on frequencies of light. The highest percentage of the polymerized monomer particles is obtained at the wavelength of 450–490 nm, reaching a maximum at 468 nm. Free-radical polymerization of methacrylate monomers used in the composite materials is initiated by stimulation of appropriate photoinitiators by light. They affect the transmission of light, the kinetics of polymerization and on complete conversion of monomer into polymer, i.e. the main properties of the material.

Many of the commercially available composite materials containing two-methacrylate resins are cured by irradiation with visible light. In the 1990s the most commonly used photoinitiator was camphorquinone – CQ (bornanedione 1,7,7-trimethylbicyclo [2.2.1] heptane-2,3-dione). During this time, virtually all curing lights used halogen lamps which generate a relatively wide range of radiation (370–515 nm) [1]. CQ absorption spectrum with a maximum around 465 nm perfectly fits the spectral emission range of halogen light. The only definite disadvantage associated with CQ is its intensive yellow color, which threatens the overall aesthetic of reconstruction with composite materials. CQ concentration must be kept to a minimum to reduce the intense yellow color effect while maintaining the desired color of the material. Reduced CQ concentration is one of the factors contributing to the deterioration of mechanical properties of composite material [2]. In order to solve this problem, producers sought an alternative in the form of PPD (phenyl-propanedione), or acrylphosphineoxides (APO), which absorb at lower wave lengths [3].

The newer generation of photoinitiators are based on iodonium salts [4], onion compounds [5] or a photoinitiator system such as Norrish Type I – acylphosphine oxide [6, 7]. They are introduced either synergistically with CQ or as stand-alone photoinitiating systems [8]. Acylphosphine oxide-based photoinitiators, such as TPO require amino co-initiators that absorb light wavelengths of shorter length (< 400 nm) than CQ, which increases their aesthetic potential. Furthermore, the initiators have additional advantages such as better polymerization kinetics and mechanical properties, which makes them an alternative to CQ.

Manufactured curing lamps differ in many features, such as: light source, the effectiveness of composite material polymerization, the amount of released thermal energy, the quality and type of optical elements, the presence of voltage stabilizer.

These features affect the quality of the emitted light, and consequently the course of the polymerization process.

Currently used equipment for polymerization of composite materials should be divided into four groups:

– halogen lamps,
– xenon (plasma) lamps,
– semiconductor lamps (LED),
– argon (laser) lamps.

Halogen Lamps

Halogen lamps have been used for polymerization for more than thirty years. The wavelength of the optical radiation emitted by halogen lamps is about 360 nm to about 560 nm, and the peak of its intensity is in the range of 400–500 nm [9–11]. The power currently produced halogen lamps is 700–800 mW/cm^2, although there are also lamps whose power exceeds 1500 mW/cm^2 e.g. Virtuoso Phase II (Denmat) – 1600 mW/cm^2 or Swiss Master (EMS) – 3000 mW/cm^2. In recent years, the market offer has been enriched with lamps of variable intensity, with a soft-start system e.g. Astralis 7 and 10 from Ivoclar Vivadent or Elipar Trilight from ESPE company. Studies have shown that the 'soft start' technique allows for a significant reduction in polymerization shrinkage of composite material. Astralis 7 and 10 lamps in the "pulse" program perform a linear increase in the light intensity from 150 to 400 mW/cm^2 in the first 15 seconds, and then the values oscillate between 400 and 750 mW/cm^2 for a further 25 seconds. For the Elipar lamp, polymerization starts with light of 100 mW/cm^2, and in 15 seconds the intensity is raised to 800 mW/cm^2, whereas hardening of the material takes 40 seconds. Both Elipar and Astralis lamps have additional programs for polymerization by light of a constant value of 400 and 750 mW/cm^2 (Astralis) and 800 mW/cm^2 (Elipar) [12].

The main problem associated with the use of halogen lamps is relatively fast wear of the bulb and filter, as well as gradual degradation of the optical system, resulting in increased heat generation and reduced efficiency of polymerization [13]. Damaged filter may result in emission of the optical wavelength in the ultraviolet range, which is particularly dangerous for soft tissues.

Xenon (Plasma) Lamps

The light source consists of two tungsten electrodes separated by a small distance, operating in a chamber filled with high-pressure gas, having a synthetic sapphire window through which the light output was directed from a parabolic reflective surface [14]. Between the two electrodes a high electrical potential is created, which ionizes the gas during formation of a spark, and provides a conductive path (plasma) between the electrodes. When the initial spark is created, the electronic system adjusts the working current in order to maintain the production of light by a variety of advanced reflexive compression systems. The gas used in plasma devices consists of argon, but it had an extremely high output power is capable of replacing 40–60 seconds of QTH (quartz-tungsten-halogen) light exposure. Plasma devices had to be highly filtered because they generated huge amounts of infrared light, which resulted in increased temperature in the tooth's tissues, and increased emission of ultraviolet light (dangerous ozone formation). They were used for curing UV-polymerized resins. Typical power of this type of light was close to 2000 mW/cm^2, and the light was broad-band from 380 to 500 nm with the peak around 460 nm, which is optimal for polymerization of composite materials. The advantage of plasma lamps is very short curing time of composite materials – around 3–5 seconds. Some studies [15–17] demonstrate that it is as effective as halogen polymerization for 40–60 seconds. However, the rapid progress of polymerization raises certain doubts, which may cause a significant increase in shrinkage of the material [18–20] and may also cause adverse temperature rise in the tooth's pulp. When choosing lamps, the cost factor is also significant. Plasma lamps are about 10 times more expensive compared to halogen ones.

QTH High Intensity Lamps

Quartz-tungsten-halogen sources competed with plasma devices by using a variety of mechanisms to increase the total capacity of their equipment. Manufacturers argued that they would certainly match plasma devices. Firstly, the curing abilities of the sources were available for increased light power at normal values. This mechanism introduced the filament (fiber) to a higher voltage, extending adopted limits more than the producers expected. Curing in this power mode was not longer than 10 seconds, because longer exposure would seriously impair the operating strength of the unit. Another mechanism that increased the power was the "turbo tip". It was a non-susceptible bundle of glass fibers, that were stretched under the influence of heat, causing the effect that the diameter of the beam was smaller at the emitting end than on the receiving end. Thus, the same amount of energy occurred at both ends but it was divided by the much smaller area of the emitting end, which resulted in about 1.6 times higher radiation [21]. This type of end bit is currently used in LED devices in order to increase the total power values. However, despite these features, the power of units with a QTH source is not equal to typical fiber s of plasma lamps and manufacturers are withdrawing from their production. The U.S. government has determined that the devices must disappear from the market in case of 100 W light bulbs in 2012, and in case of 40 W sources by the end of 2014 [22].

With increasing radiation of applied curing lamps, a new problem appeared with the application of excess heat in the direction of the teeth and soft tissues in the oral cavity. It turned out that with such high light intensity in plasma lamps, high shrinkage because the resin is polymerized so rapidly that it blocks the relaxation process in the polymerized network before vitrification.

In order to overcome this problem, it was proved that if the power (intensity) of light is provided while controlling the speed of curing, relaxation will occur through liberation of resin flow before vitrification. It was expected that in this way a much smaller breakage of continuity in the connection on the border between filling hard tissues of the tooth would appear [23]. In addition, less heat would be generated in the tissue during the restoration process [24]. Small differences were also observed in studies on microleakage consequently leading to complications with postoperative hypersensitivity, discoloration and secondary caries [25–27].

The Soft-Start Technique

It involves initiation of polymerization with low-intensity light and continuation of curing with high-intensity light. Initially, the above mentioned method was connected with QTH sources, resulting in the use of sources with initial 10 second start at low power of about 100 mW/cm^2 with immediately following jump to the maximum output for the remaining exposure time [28]. Subsequent changes resulted in increased time of the initial exposure, with following exposure time at full power. However, after first clinical observations it turned out that this technique has not brought the expected significant reduction of stress in the structure of composite material [29]. This speeded up the search for other methods of polymerization. A significant reduction in shrinkage can be achieved by using a two-step pulse technique (pulse-delay curing), in which the last layer of composite material was subjected to low-power short-time exposure (3 seconds at 200 mW/cm^2). It was recommended that doctors receive another patient for 5–10 minutes, while the composite material flowed in and relaxed internal stress, then a dose of high-energy light was administered to complete the bonding of material for 30 seconds at 500 mW/cm² [30]. A specially designed lamp is produced by, among other manufacturers, BISCO company under the name New VIP® (Variable Intensity Polymerizer) with light intensity in the range of 100 to 600 mW/cm², and with exposure time adjustment from 2 to 255 seconds and two polymerization programs: P1 – low-energy, light intensity 200 mW/cm², exposure time 3 seconds, P2 – high-energy, light intensity 600 mW/cm², exposure time 30 seconds. Another device is Astralis 7 from Ivoclar Vivadent with three programs: LOP (Low Power Program) with 400 mW/cm² light intensity, HIP (High Power Program) with light intensity of 750 mW/cm², PUL (Pulse Program) where during the first 15 seconds the light intensity rises from 150 mW/cm² to 400 mW/cm², then for 25 seconds it changes in a pulsatile manner in the range from 400 mW/cm² to 750 mW/cm². However, the application of these lamps did not produce stunning results when compared with conventional procedures [30].

This type of light exposure is equivalent to providing energy directly to the farther layers of the applied material. So probably a correlation between increasing marginal adaptation, reduction in polymerization shrinkage and lowering internal tensions by using the above described procedure could be associated with a lower total degree of hardening of the bottom layer of the material [31, 32]. Sakaguchi [33] suggests that as long as the appropriate irradiation is used, during the high-power phase the degree of polymerization of the lower layers should not be a problem.

In many modern curing lamps various soft-start techniques are used, even in LED lamps. A comparison of composite material's conversion process at 40-second irradiation demonstrated that the soft-start procedure showed no significant difference [34], however the shrinkage tension and the temperature rise during polymerization decreased [34, 35].

In order to remain on the market, manufacturers of plasma lamps needed to reduce the high level of internal tension and temperature rise in devices [36] so they tried to use the soft-start technique, but the properties of plasma lamps did not allow for the possibility of working at lower radiation power, because a spark generated from even the minimum voltage produced more light than conventional quartz-tungsten-halogen sources with adjustable power. Thus, the benefits resulting from the soft-start of technology could not be implemented in plasma lamp units [37].

Light-Emitting Diodes

Blue radiation was developed in the early 90s of XX century with the use of indium gallium nitride substrates (InGaN) [38]. It was also the color that allowed the emergence of the first white LED [38, 39]. Light-emitting diodes are semiconductor devices, which are based on the polymerization energy difference towards conducting (forbidden band) between two different semiconductor substrates (n-type conduction band and p-type valence band) to determine the wavelength of the emitted light [14]. These devices are much more efficient, effective and are much lighter than previous types of dental light sources.

LEDs first appeared on the market at the end of 2000, for instance LUX MAX® (Akeda Dental A/S, Lystrup, Denmark). The lamp consisted of many individual LED element clusters of 5 mm (each chip delivered 30–60 mW) gathered axially or positioned on a plane in such an arrangement that the combined power was sufficient to provide the energy required to activate a CQ photoinitiator. A higher efficiency of LEDs was achieved compared to conventional halogen lamp units. This was related to the amount of radiation emitted within the range of maximum absorption of CQ. LED lamps provided much more power within the region (450–470 nm) compared to halogen lamps [40], which translated into appropriate hardening of resin in shorter time with LEDs that provided less measurable power than longer exposure to halogen light emitting more total power.

The total curing potential of the first generation LED lamps was much lower than the lamps used at the time. In early 2000 s, manufacturers of dental equipment built into the lights new 3-W chips characterized by certain wavelengths, which consumed 1 W or more power. Two types of chips were available: the 1 W chip (Luxeon LXHL--BRD1 or MRDI generating 140 mW of power), and the 5 W chip (Luxeon LXHL-PRDS or MRDS generating 600 mW of power). A characteristic feature of these units was a significant increase in output compared to the device of the first generation [38], as a single 5 W chip provided a similar amount of luminance as 10–20 typical individual 5 mm diodes of the first generation devices (LED). However, a similar wavelength power range was created in the same way as in the first generation devices. The technology was improved by introducing nickel-metal hydride battery, which acted as the main energy source. This resulted in increased amount of energy in a small area and, consequently, temperature rise inside the system, which could cause permanent damage [41]. Therefore, the unit had metal heat sinks and surfaces dissipating heat from chips [38, 42].

In addition, fans were reintroduced to the second generation LED, which in turn meant that they became competitive in the curing device market [43, 44].

Third-Generation LEDs

In order to allow the use of not only camphorquinone photoinitiator, which is an activator of 450–490 nm waves as the most common initiator of the polymerization reaction, the manufacturers have introduced LEDs to chip sets that emitted more than one wavelength [45], for example Ultralume® 5, Ultradent Products, central 5 W chip, blue LED surrounded by four low-power violet LEDs (approximately 400 nm) with the result that a device consisting of two wavelengths was effective not only for the camphorquinone photoinitiator, but also for an alternative set of photoinitiators, which was equivalent to broadband LED curing lamps. Other manufacturers introduced violet chips along with other blue chips inside a single LED element: LZ4-00D110, High Efficiency Dental Bluet UV LED Emitter, LED Engin INC with 1UV matrix emitting 0.76 W and with three 3 blue matrices, each emitting 3 W. The ability to generate different wavelengths by a single LED was the main feature of the third generation LEDs.

This generation of LED devices are able to effectively provide sufficient radiation at the appropriate wavelengths for polymerization of each type of filling material. Operating these devices is comfortable and safe as well as they are attractively priced.

Laser (Argon) Lamps

They constitute the least popular group of devices used for curing composite materials. They emit waves of seven different lengths from 457.9 to 514 nm.

Initially the laser energy was delivered directly to the tooth by the end of the optical fiber cable. However, because of the divergent nature of the radiation, other methods were developed to obtain a parallel beam of coherent energy radiation, whose effect will not be associated with the distance between the tip of the device and the tooth, as was the case in conventional plasma optical fibers. Initially, the size and area occupied by the lasers were very large. But a single source could be adjusted so that a single laser could supply many operators using fiber optic cabling. Over time, the laser size was reduced so that it could easily fit in the surgery. However, due to the high cost and the fact that only clinicians – and not auxiliary staff – could operate the device, the laser had limited use.

According to Powell [46] by using an argon laser one can get a similar polymerization effect four times faster than using a traditional halogen lamp. The laser device should operate at its optimum power in the range from 250 mW to 350 mW for 10 seconds.

Materials polymerized with argon laser light are characterized by at least as good strength parameters as materials polymerized with halogen lamps [47].

The disadvantages of an argon laser as curing light source include violent character of the polymerization process, which can cause cracking of the enamel or the possibility of enamel break-off on the edge and formation of a fissure between the material and hard tissues of the tooth. It was proved that high-speed pulsation of light secures a better filling surface and deeper conversion with continuous expansion. Some researchers believe that for each type or shade of composite material, or for the distance between the tip of the device and the filling, individualized energy supply should be selected in order to obtain the most optimal effect.

Conclusions

Among practicing dentists, the most popular materials used for reconstruction of lost hard tissues of teeth are light-cured composite materials polymerized by various light sources. The most popular ones are halogen lamps. Plasma lamps are characterized by very short curing time (3–5 seconds) of composite materials, and effectiveness equal to that of polymerization with halogen lamp, but rapid polymerization and high cost of the device raise doubts.

Semiconductor LED lamps saw the third generation, and are enjoying more and more popularity because their effective working time is more than 200 times longer than that of halogen lights. Compared with halogen lamps, they are characterized by lower energy consumption, higher operational efficiency with low intensity of radiation.

The least popular are argon (laser) lamps, especially due to the high cost of equipment, inability to be used by auxiliary staff and a significant increase in the room temperature resulting from the working unit.

It should be expected that the immediate future will show the direction in which the technologies related to the polymerization of composite materials will develop.

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