Light-curing of resin-based restorative materials: an evidence-based approach to clinical practice application

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Abstract: The process of light-curing resin-based dental materials is one of the major reasons for clinical failures. However, there is a lack of information and instructions on what is required to achieve an adequate light-curing in different clinical situations. Thus, the present literature review aims at providing a brief background on light-curing in Dentistry and some recommendations to help on different light-curing processes used in the clinical routine on a daily basis. **Keywords:** Light-curing. Curing lights. Dental curing lights. Photoinitiators.

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INTRODUCTION

Over the past decade, there has been a vast increase in dental restorations worldwide. More than half of a billion dental restorations are made each year, together with the exponential growth of the dental market sales.[1,2] However, the average lifespan of a dental restoration still remains a challenge. Perhaps the most serious drawback of the dental restoration's clinical performance is the photopolymerization procedure.

A poorly polymerized restoration may result in premature clinical failure because of marginal defects, secondary caries or restoration fracture.[3,4] In addition, the biocompatibility of the restoration is adversely affected when the resin is under-cured,[4] because components of the resin and initiator system may leak out of the restoration. Therefore, the objective of the present work is to review the different factors affecting the photopolymerization efficiency of resin-based dental materials with a critical appraisal of the different clinical implications of using resin-based materials with different photoinitiators systems.

BASIC PRINCIPLES OF PHOTOPOLYMERIZATION REACTIONS

Photopolymerization is a chemical reaction where the process of initiation starts using light for the reaction of monomer molecules to form polymer chains or three-dimensional networks.[5] The basic idea is to readily transform a liquid monomer into a solid polymer after light exposure. As a photopolymerization reaction involves a photoinitiator system, a polymerizable medium (monomers), and a light source, a strong interplay should exist between them. In the dental clinical environment, the photopolymerization is a clinical procedure that is performed in order to initiate polymerization reaction of resin-based materials such as dental adhesives, luting cements and resin composites. The light exposure is capable of exciting the photoinitiator system present in the resin-based material to generate free radicals and thus start the polymerization of the material.

Photoinitiator Systems

The photoinitiator systems present in the commercial materials can be of two types: Norrish Type I photoinitiators which generate free radicals by cleavage reaction, i.e. by dissociation of the photoinitiator in one or more parts, thus generating two or more free radicals;[6] or, Norrish Type II photoinitiators, such as Camphorquinone (CQ), which reacts with a co-initiator that generates a free radical capable of initiating the polymerization reaction.[6]

The photoinitiator system used in most dental resin materials is CQ.[7] However, CQ has a yellowish coloration (Fig 1) that is capable of affecting the color of the resin materials and, consequently, limiting the manufacture of products with lighter colorations.[7] In addition, CQ, as a Norrish Type II photoinitiator, requires the use of a co-initiator. This co-initiator, usually a tertiary amine, undergoes oxidation over time. The oxidation of the co-initiator changes the color of the resin and may affect the esthetics of restorations in long term.[8]

For those reasons, alternative photoinitiator systems to CQ have been studied and even used in the formulation of commercial products, such as trimethylphosphinic oxide (TPO) and benzoyl germanium (Ivocerin®) (Fig 1).[9,10] However, for light curing these alternative photoinitiator systems, dental light curing units with violet light emission are essential. Each photoinitiator system is capable of absorbing a specific light spectrum (violet, blue, etc.). As can be seen in Figure

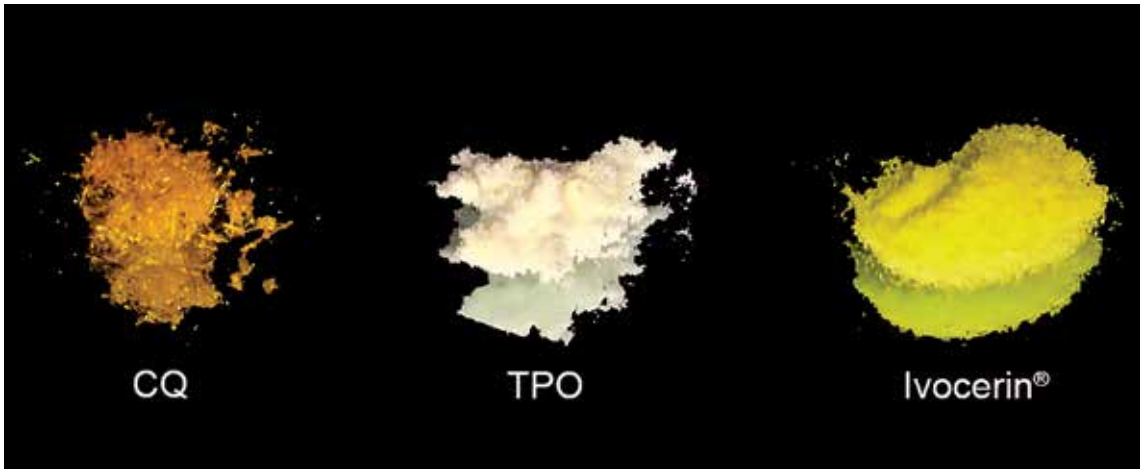

Figure 1: Photoinitiators used in dental materials: camphorquinone (CQ), trimethylphosphinic oxide (TPO) and benzoyl germanium (Ivocerin®).

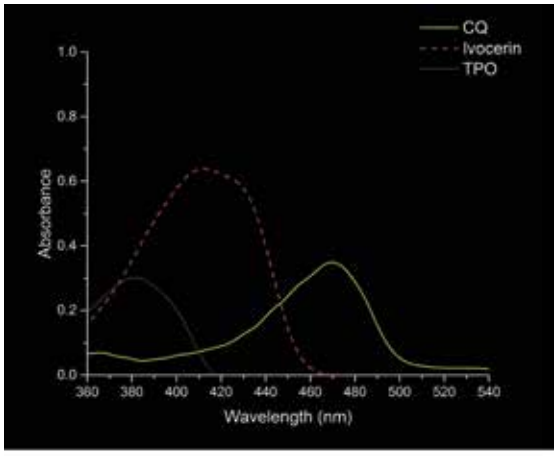

Figure 2: Absorbance of different photoinitiators versus light wavelength.

2, CQ absorbs light in the blue light spectrum, with absorption peak at approximately 468 nm. While photoinitiator systems such as, TPO and Ivocerin® absorb violet light, and when the violet light spectrum is not emitted by the dental light curing unit, the photoinitiator system does not generate free radicals efficiently, reducing the polymerization of the resin material.

Dental curing lights

The light curing in Dentistry began in the 70's with the use of ultraviolet light (UV) (Nuva Light, Dentsply / Caulk) to polymerize resin materials. But this polymerization system did not remain in the market due to the great health risks caused by UV light.[11] In the 80s, advances in the field of visible light polymerization allowed the development of resin materials photopolymerized by blue light and the halogen dental curing lights began to be used for light curing.[11]

Halogen lamps emit the entire visible spectral range from an incandescent light bulb and violet and blue light are filtered by a prism.[12] But, halogen dental curing lights have disadvantages in terms of portability because the size of the equipment, since the incandescent energy generates heat and that heat needs to be dissipated by cooling systems such as the fans, and the need for wires, since the incandescent lamps

have high power (≈ 80 W), and require high energy flow from a source with a voltage of 110 to 220 V. In addition, these devices require the annual replacement of the tungsten lamp, because the average life of an incandescent lamp is approximately 50 hours and assuming there is approximately 12 minutes of daily use for 250 days a year.[13]

In 1995, the use of light emitting diode devices or LEDs was suggested for dental applications. The LEDs provided several advantages compared to halogen lamps, such as the lower heat generation due to the conversion of electric energy into light and the greater portability because they consume much less energy (< 2W). This allows battery driven units, and thus allows the manufactures to build devices with designs that allow better access to the inside of the oral cavity.[14]

The LEDs made possible a great advance in light curing in dentistry. The first and second generations of LED light curing units (LCU), also called monowave LCU, emitted only blue light, the light spectrum absorbed by Camphorquinone.[4,11] Subsequently, with the inclusion of other photoinitiator systems with absorption in different light spectra, LED LCUs with emission of more than one light spectrum were released into the market. These LCUs, also known as polywaves® or multiwave LCUs, are photoactivating devices made up of a combination of 2 or more LED chips emitting in different bands of light spectrum (Figs 3 and 4).[4,11,15]

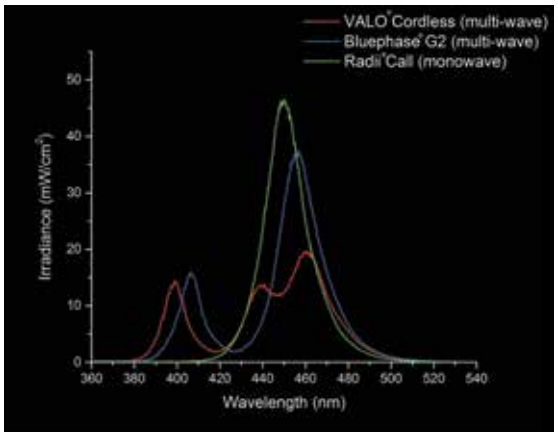

Figure 3: Irradiance of monowave and multiwave LEDs versus wavelength emittance.

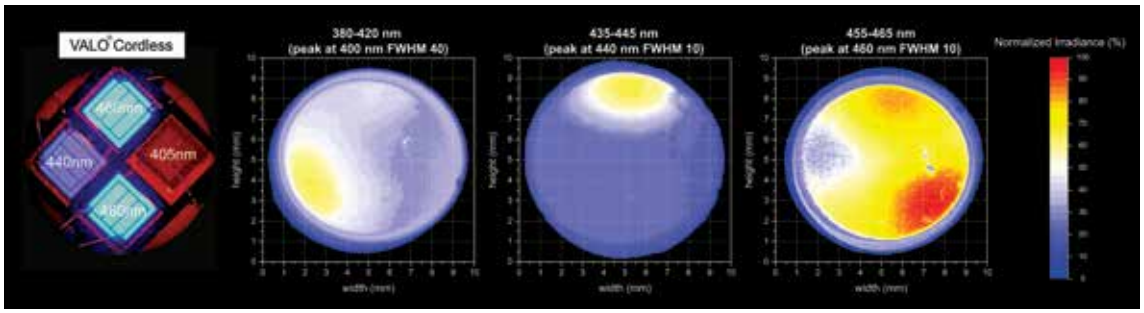

Figure 4: Beam profile of VALO® Cordless according to its different LED emittances.

CLINICAL IMPLICATIONS OF THE PHOTOPOLYMERIZATION PROCESS

The photoinitiator has a crucial role as it absorbs the light, converts the energy into reactive species (free radicals) to start the reaction and its reactivity governs the efficiency of the polymerization. However, many clinical implications have been highlighted regarding the use of the CQ-amine photoinitiator system. As a highly yellowish molecule, CQ directly influences on the shade of resin-based materials, limiting fabrication of whiter or more translucent shades.[7,8] Moreover, as a Norrish type II photoinitiator, CQ needs a co-initiator, such as tertiary amines, to react and create free radicals that are responsible for initiating the polymerization. As highly reactive molecules, remaining amines can oxidize, producing a yellowing effect on resin materials over time, and thus, causing color change in long term.[8]

Also, the disadvantages of the CQ-amine photoinitiators concern the toxicity of the used amines.[16] Furthermore, in a Norrish Type II two-component photoinitiator system, the interaction of the initiator and co-initiator is strongly influenced by the viscosity of the medium.[17]

On the other hand, Norrish Type I photoinitiators do not require an amine-based co-initiator to generate free radicals and they are usually light-colored molecules.[6,7] These photoinitiator systems, called "amine-free", such as the phenylbis (2,4,6-trimethylbenzoyl), phosphine oxide, also known as TPO, and the new germanium-based photoinitiator, commercially known as Ivocerin®, may substitute the CQ in dental resin-based materials.[9] As a result, if used in resin materials, they would allow whiter or more translucent shades as well as to reduce the yellowing in the long term, as claimed by the manufactures.

However, it is important to highlight that despite the esthetic benefits, these Norrish type I photoinitiators primarily absorb light into the violet spectrum rather than light into the blue spectrum, such as CQ does.[10,17] The concern is that violet light is not transmitted as deep as the blue light, thus causing possible problems in the degree of conversion in deep layers of some resin materials, as already described in literature.[7,9]

The following part of this paper moves on to describe in greater detail the clinical implication of photoinitiator systems in dental adhesives, resin cements, resin-based composites and Bulk fill composites.

Adhesive systems and its water-based composition incompatibility

It is well established from a variety of studies that two steps self-etch (2SE) and three steps etch and rinse (3ER) adhesives have better clinical performance than one step self-etch (1SE) and two steps etch and rinse (2ER) adhesives.[2] There are many reasons to explain why these classes of adhesives perform differently, however what it is almost certain is that the adhesives that have a separate bottle containing the hydrophobic part of the adhesive, also called the "bond" bottle, seem to behave differently. The hydrophobic part of the adhesive system might be one of the major reasons for the better performance of these dental adhesives. This distinction between these classes of adhesives is further exemplified in studies using an additional layer of hydrophobic resin coat on top of the dental adhesive layer.[18] This effect may partly be explained by the CQ-amine photoinitiator behavior that seems to perform really well in low-viscosity hydrophobic polymerizable liquids likewise the "bond" part of 2SE and 3ER dental adhesive. On the other hand, in water-based

or acidic dental compositions, such as 1SE and 2ER, the hydrophobic behavior of CQ and the acid–base reaction of acidic monomers used in these materials with the amine-based co-initiator affects the initiating efficiency of the CQ-amine photoinitiator system, thus affecting the polymerization of these adhesives.[19,20]

Recent evidences suggest that Norrish Type I photoinitiators could be used as an alternative photoinitiator to the CQ-amine photoinitiator system in 'mild' and 'ultra-mild' self-etch dental adhesives when they are cured with a multiwave LED.[19,20] However, contrary to expectations, these studies did not find significant differences between CQ-amine and TPO, even further, CQ-amine is still the better option regarding dental adhesive photoinitiators. Especially because, not only DC and monomer-release determine the biocompatibility of adhesives, but also the cytotoxicity of the photoinitiator. It has been proven that similar adhesive formulations containing TPO are more toxic than the ones containing CQ-amine alone.[21]

A more comprehensive study would include all Norrish Type I photoinitiator systems (i.e. Ivocerin and BAPO) to assure that CQ-amine system is still the better option for dental adhesive. Thus far, 2SE and 3ER containing CQ-amine photoinitiator system are the most reliable dental adhesives for clinical application and they both can be cured properly using either monowave or multiwave LCUs.

Amine free resin cements, does it really worth it?

Several factors can affect the adequate light curing of indirect restorations, among them the type, color and thickness of the resin composite or ceramic used.[22,23] In a direct relationship, the greater the light transmission capacity of the resin composite or the ceramic, the greater the amount of energy that reaches the underlying cement. For this reason, sometimes higher light curing exposure time is indicated for some types and thicknesses of resin composites or ceramics.

However, very thin ceramic restoration, also described as laminated veneers, are becoming very popular and CQ-based resin cements might limit the clinical application.[24,25] Laminate veneers are translucent ceramics with less than 0.5 mm thickness, thus not being an important barrier that would reduce light transmittance to the resin luting cement right below it. Despite the fact that the combination of CQ with alternative photoinitiators be the best way to improve esthetics without affecting properties, many manufactures have been launching the so called "amine-free" resin cements into the market. It is obvious that translucent and clear shades of resin cements to be used to lute very thin lenses veneers would not be a problem. Moreover, these resin cements are supposed to be translucent, another point that is important to highlight, since it allows light-transmittance through the resin cement layer itself. On the other hand, shaded resin cements contain pigments to give its color (i.e.: A2), these pigments absorb light, reducing the amount of light that is transmitted through the resin cement layer.

The problem is that sometimes manufactures exceed the indications or, even worse, omit to let the user know the limitations of these resin cements. Then, when used with ceramic veneers that are not translucent and/or are thick, light-transmittance is affected and, the resin cement does not polymerize properly. Of course, as shaded and thicker the ceramic veneer, the lower is the light-transmittance to the resin cement layer. Still, as shaded the resin cement,

the lower is the light-transmittance through the resin cement layer. Therefore, it is important to balance when the benefits of using "amine-free" resin-cements are required and, understand and ponder the limitations of their clinical indications according to different clinical scenarios.

Resin Composites: Is it the color change a really a problem for CQ-amine-based composites?

As previously stated, CQ is a highly yellow colored molecule that affect the shade of resin-based materials, limiting fabrication of whiter or more translucent shades. However, during photopolymerization CQ absorbs visible light, interacts with a co-initiator and the CQ's chromophore group is transformed, thus decomposing CQ into a colorless product. This phenomenon is known as the photobleaching effect.[26] However, the CQ photobleaching depends on the consumption of the CQ that its related to many factors, but the most important is the concentration of CQ in the resin material.[27]

The concentration of initiators not only influences color, but it also plays a role with fundamental properties of resin-based composites. Especially because, excessive concentrations of the chromophore CQ may behave similarly to a blue light filter, keeping the light from reaching deeper portions of the restoration.[28] The clinical implications regarding light transmittance through the resin-based composite and as consequence the depth of cure of these composites will be further explained on the next section of Bulk fill composites.

However, some manufactures try to overcome this problem by reducing CQ concentration without reducing efficiency. This is possible if a phenyl iodonium salt additive or Norrish Type I photoinitiators are combined with CQ-amine as the photoinitiator system.[29,30] The combination of these initiators has been proven to be efficient to reduce the initial yellowness of the composites as well as to reduce the photobleaching effect, making it easier to match the color between the composite and the original tooth, especially those ones that received dental bleaching treatment.

However, this approach must be followed with caution because despite the initial benefit upon easier color matching, the influence of these combinations on color stability in long term is not well established. Moreover, is already known that Norrish Type I photoinitiators tends to bleach over time, which would also cause color mismatch in long term.[7,8]

Bulk fill Composites: improved photopolymerization for faster restorative procedures and its consequences.

The concepts of Bulk fill composites and high power dental curing lights are central to understand how dentists seems to be eager to perform direct restorations faster.[31] Saving time during a restorative procedure is really convenient, but perhaps inadequate polymerization throughout the restoration is the most serious disadvantage of this method using bulk increments.

Bulk fill composites are light-cured, resin-based materials used for direct restorations of posterior teeth that can be placed in increments of 4 mm to 5 mm thickness.[9] The higher depth of cure of these composites in comparison to regular resin composites can be related not only to modifications in their monomers and filler compositions, but also in the photoinitiator system used.[9]

One possible explanation for this is that these "alternative" photoinitiators are more re-

active than CQ, and they also produce more free radicals capable of initiating the polymerization, thus increasing the degree of conversion.[6,9,17] However, these "alternative" photoinitiators generally absorb violet light, which has a lower transmittance in comparison to blue light, thus, increasing the degree of conversion on the top of the restoration, but not contributing to increase the depth of cure of the composite.[9] However, taken together, these results suggest that the increase in degree of conversion on the top would increase the refractive index of the polymer formed. This would reduce the mismatch between the resin and filler refractive indices, improving the transmission of blue light to the deeper portions of the restoration, thus, enhancing the free radicals formation by the CQ-amine photoinitiator system at the bottom part of the restoration. This would then increase the depth of cure as claimed.[32]

A serious weakness with this argument, however, is that the dental curing lights, specially the multiwave LCUs do not emit a homogeneous light beam, thus some areas of the restoration could remain under-cured.[4,9,15] As shown in Figure 5, a Class II restoration light cured with a multiwave LED that has an inhomogeneous light beam emission would create under-cured areas under the violet light emission area.[33-36] Also, it could be even worse if a Bulk fill composite containing CQ combined with Norrish Type I photoinitiators was light cured with a monowave LED, because the amount of CQ is reduced when combined with other photoinitiators, reducing the photopolymerization efficiency in depth.[9]

Another significant aspect of Bulk fill composites is the polymerization shrinkage stress. In vitro studies have shown that Bulk fill composite restorations might fail due to internal gap formations or by enamel cracks formed nearby

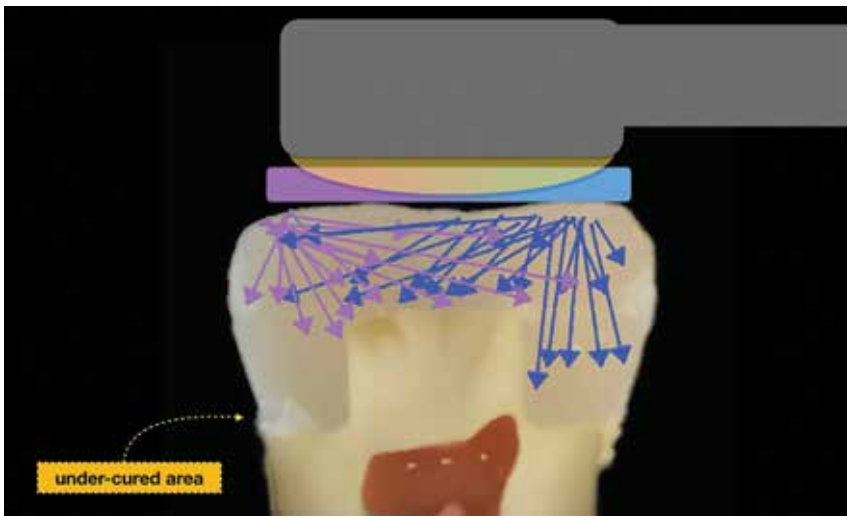

Figure 5: Schematic illustration of light scattering of a multiwave light through the composite in a Class II restoration.

restoration margins, possibly correlated to the polymerization shrinkage stress of the Bulk composite.[37] Moreover, clinical evidence has shown that Bulk fill composites containing CQ-amine as the only photoinitiator presented an annual failure rate of 2.0%, while Bulk fill composites containing CQ-amine combined with TPO presented an annual failure rate of 4.65%.[38] This means that the annual failure rate has doubled when CQ was combined with TPO. In addition, the main reason for these failures was secondary caries, which is often associated with the marginal adaptation of the restoration.

It is almost certain that the polymerization reaction produces stress that would not be adequately dissipated by the strain caused within the composite, even in Bulk fill composites. Therefore, it is probable that the stress is transferred to the bonded interfaces with the tooth structure creating delamination or tooth fracture whenever and wherever the localized stress exceeds the adhesion strength or the strength of the adjacent residual tooth structure. Furthermore, these stresses may increase with time, causing delayed damage to cavity margins.[38] The findings indicate that CQ-amine and TPO Bulk fill composites could yield a higher polymerization shrinkage stress than CQ-amine Bulk fill composites. This suggests a weak link may exist between polymerization shrinkage stress and the clinical performance of Bulk fill composites containing CQ-amine associated with TPO.

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