Factors influencing success of radiant exposure in light-curing posterior dental composite in the clinical setting

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ABSTRACT: Purposes: (1) To conduct a comprehensive review of the literature on factors influencing the radiant exposure of resin-based composite (RBC) restorations and (2) To fully understand the appropriate way of using the light curing units (LCUs) to perform restorations with optimal mechanical/physical properties. **Methods:** A PubMed search identified recent publications in English that addressed the factors affecting the longevity of the RBC restorations and the optimal usage of LCUs. **Results:** RBCs require light-induced polymerization of methacrylate monomers present in its composition to reach acceptable mechanical and physical properties. Complete polymerization of the RBC is never reached, and the maximum degree of conversion (DC) varies from 40 to 80%. The amount of radiant exposure (Joules/cm²) required for the commencement of polymerization becomes a core driver for the quality of the RBCs. Insufficient radiant exposure may lead to low strength behavior and susceptibility to degradation, thereby shortening the lifespan of restorations inside the mouth. This suggests that there are factors affecting the radiant exposure during clinical procedures; these factors can be categorized as material-related, LCU-related and operator-related factors. (*Am J Dent* 2018;31:320-328).

CLINICAL SIGNIFICANCE: Proper light-curing techniques are critical for delivering an adequate amount of radiant exposure to RBCs. Adequate light curing decreases the number of underexposed RBC restorations, improves their mechanical and physical properties and accordingly, increases their clinical longevity.

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Introduction

Light cured resin-based composites (RBCs) were first introduced in the 1960's, and since then have become the most popular restorative material due to their esthetic properties and conservative technique that minimize the amount of tissue removal prior to restoration placement.[1]

Some clinical studies have reported shorter longevity and higher failure rates for RBCs compared to other restorative dental materials. A longitudinal study[2] evaluated the survival rate of RBCs in posterior teeth and found an annual failure rate (AFR) of 1.6%.[2] The results of a systematic review[3] evaluating the longevity of posterior RBCs in adults demonstrated similar AFR of 1.55%. As a result, the replacement of these restorations is very frequent in dental practices.[4] Moreover, RBC replacements contributed up to 60% of operative work[5] and RBCs were found to fail two times more than their amalgam counterparts.[6] Furthermore, a systematic review[7] found a total failure rate of 24.1% associated with anterior RBCs. The main causes of failure were related to fracture and secondary caries.[8-10] It is highly possible that the root cause of failure is the lack of adequate radiant exposure when curing RBCs.[11,12] Price et al[13] measured the radiant exposure delivered by 20 operators. The practitioners delivered less than 10 J/cm^2 to RBCs placed over class I (5-35% of practitioners) and class V cavity preparations (30-75% of the practitioners). Moreover, Watts et al[14] reported that only 46% of the published studies between 2010-2012 stated the amount of radiant exposure that was delivered in their experiments, which questions the validity of the other experiments in this time frame. Insufficient radiant exposure was found to be associated with low mechanical/physical properties,[15-20] more bacterial colonization,[21] lower bond strength,[22,23] and less color stability.[24,25]

Recent studies[26,27] reported equal or even superior performance of RBCs compared to amalgam, which implies that RBC could have a clinical performance and survival rate similar to amalgam when placed appropriately. To improve the longevity of RBCs, clinicians should first have a firm grasp of why these restorative failures occur.[28]

In order to investigate the factors affecting radiant exposure and their impact on increasing the longevity of the RBC, the following review was developed to summarize the importance of each factor and how it affects the outcome of the restorative work.

THE CONCEPT OF LIGHT CURING

Adequate light-curing is not only required for light-activated RBCs to achieve their manufacturer's intended properties, but it is also believed to be an essential requirement for predictable long-term clinical success.[11] Almost the entire group of RBCs uses the same basic monomer family (methacrylate and vinyl) and polymerization mechanism (free radical addition polymerization).[29]

The photopolymerization effect is based on the interaction between the photoinitiator, light cure energy, and monomers. Photopolymerization is described in three stages: initiation, propagation, and termination. First, when the visible light with compatible emission spectra is activated, photoinitiators inside the RBC absorb photons of a specific wavelength and generate free radicals. The reaction between the newly formed free radicals and surrounding monomer leads to the opening of the C=C bond (initiation). The continued C=C bond opening enhances the growth of the polymer chain. The tri-dimensional growth of this polymer chain increases the cross-linking of the

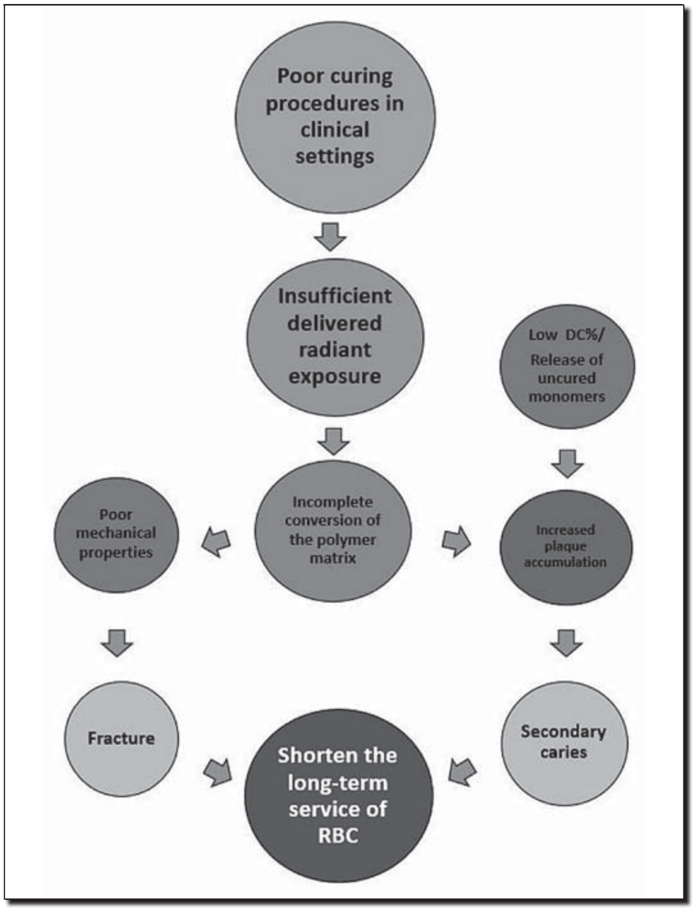

Fig. 1. Summary of the negative pathway of events triggered by poor curing procedures in the clinical setting. The outcome of RBCs failure due to fracture and secondary caries can lead to a shortened clinical service.

chain to another polymer, which promotes material rigidity (propagation). At a certain level, the reacted free radicals form a stable covalent link (termination).[29,30] Optimum efficiency is obtained when the peak absorbance of the photoinitiator corresponds with the spectral emission from the LCU.

THE RELEVANCE OF THE DEGREE OF CONVERSION (DC)

DC of a material is the extent to which the monomer is transformed into a polymer and is known as the percentage of double C=C bonds within the monomer which converts to a single C-C bond.[31,32] After RBCs were introduced, the DC was recognized to be an important factor in the success of these materials. Simple methods can be used to evaluate the DC of the external surface of composites, but the inner layers are not similarly accessible to evaluation. Therefore, an adequate cure of the entire visible light-activated restorations cannot be assumed, based on external surface properties.[33]

In the literature, variation from 40% to 80% of the DC has been shown in polymerized RBCs. An increase in the DC can improve both mechanical and physical properties of the material,[34,35] but at the same time, it might increase the polymerization shrinkage stress with an adverse effect on marginal leakage. It was recommended[31,32,36] that the DC should be increased to a percentage that balances optimum physical properties with polymerization shrinkage stress.

As a result of finding a positive correlation between the DC and mechanical behavior of RBCs in several studies,[17,37] increased DC was found to improve the material's biocompatibility by reducing the amount of residual monomer leached into the oral environment. Figure 1 illustrates a summary of the negative pathway of events triggered by poor curing procedures in the clinical settings. The outcome of RBCs failure due to fracture and secondary caries can lead to a shortened clinical service. The understanding of the influencing factors may guide clinicians to optimize curing procedures and ensure the maximum performance in the chain of events involved in the light curing process of RBCs and potentially reduce the risk factors of premature failure. Since a direct relationship between DC and radiant exposure (measured in J/cm^2) has been well established, the recommendations to clinicians were to apply high radiant exposure levels during photoactivation by increasing radiant emittance and/or exposure time.[38,39]

MATERIAL-RELATED FACTORS AFFECTING RADIANT EXPOSURE

Many factors have been stated to influence the degree of polymerization of RBC. Some of these factors include photoinitiators, light transmission, increment thickness, and filler type.[40]

Photoinitiators

Polymerization of RBC develops when the LCU activates the photoinitiators. Different RBCs require different light energy levels for proper curing as the photoinitiator activation occurs at specific wavelengths. Optimum efficiency is obtained when the peak absorbance of the photoinitiator corresponds with the spectral emission generated by the LCU.[41] During light exposure, the photoinitiator absorbs energy from photons at a specific wavelength range, facilitating its dissociation into two or more free radicals. However, the mechanism of photolysis to generate free radicals may differ depending on the choice of the initiator.[42]

Camphorquinone (CQ) is the most widely used photoinitiator in RBCs. CQ is a solid yellow diketone compound with an unbleachable chromophore group that leads to an undesirable yellowish shade in cured composite. To avoid this disadvantage, other types of photoinitiators, such as diphenyl (2,4,6-trimethyl benzoyl) phosphine oxide (TPO) and bis-acryl phosphine oxide (BAPO) are used to reduce this discoloration, especially for bleach shades.[43] TPO and BAPO absorb light at shorter wavelengths than CQ and, as a consequence, present a very pale yellow color or no color at all. BAPO and TPO are Norrish Type 1 photoinitiators, which means that they generate free radicals by a photocleavage process that does not require a co-initiator. Type 2 photoinitiators, such as CQ, need a co-initiator molecule to effectively generate free radicals, which are formed by the displacement of hydrogen from the photoinitiator.[44]

When CQ absorbs the light, it excites and interacts with the tertiary amines to form a photoexcited complex. Free radicals are produced on both CQ and tertiary amines when CQ abstracts a hydrogen atom from the tertiary amines. Figure 2A illustrates radiant emittance activating the camphorquinone to start the free radical polymerization represented by DC%. The newly formed free radicals open the C=C bonds of monomers, resulting in the formation of new radicals with a much longer chain. The same process continues through the chain reaction

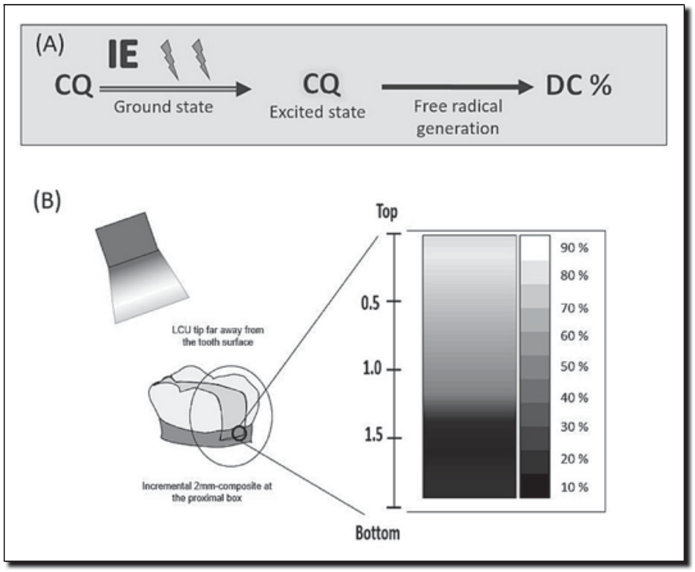

Fig. 2. **A.** Illustration of radiant emittance activating the camphorquinone to start the free radical polymerization represented by DC%. **B.** Visual representation of a gray scale mapping representing the DC% obtained from a composite increment at the bottom of the proximal box when the LCU's tip is far away from the restoration.

until the reaction process is completed. The peak sensitivity of CQ is near 470 nm in the blue wavelength range. TPO absorption spectrum extends from 380 nm to about 425 nm.[41,45]

Higher DC and hardness were reported as the concentration of photoinitiators is increased. However, it is important to note that beyond a certain concentration, shrinkage stress might be observed.[46,47] Also, incorporating photoinitiators in excess may lead to significant light absorption in the superficial layer of the restoration which could block the light transmission to the deeper layer.[46] In addition, the type and ratio of co-initiator were found to affect the amount of polymerization.[48] To date, the optimization of the ratio between such a photoinitiator and co-initiator is not reported in the literature.

Light transmission through the RBCs

After light-curing, specific particles in the restorative material become activated to convert all of its monomers into polymer resulting in a material with strong mechanical properties. However, the cure rate is not higher than 61% on the surface directly illuminated by the light source, and the DC is decreased with the increase of the depth.[49]

During this photoactivation process, the light that passes through the RBC is absorbed and scattered. The depth of cure depends on several factors including the radiant emittance, exposure time, RBC shades, translucency, and filler particle size and load (Fig 2B). The most important limiting factor for the depth of cure is light scattering, and this can be maximized when the filler particle size is close to half of the wavelength emitted by the light source.[50,51]

The literature[52] shows that RBCs of darker shades required more energy for proper curing than those of lighter shades or those designed to be more transparent. Various studies[46,53] reported that dark and opaque shades reduced light penetration to the bottom layer of composites, resulting in a reduction of the depth of cure. Several factors contribute to the light transmission through the composite including the thickness as well as the shade and contrast ratio (CR) of the composite. Thus, a material with a high contrast ratio would be relatively opaque and accordingly has lower light transmittance and lower translucency.[54,55]

Material thickness

Restoring a deep cavity with a single RBC layer that is more than 2.5 mm in thickness was reported to cause a significant reduction in the material properties that may affect its clinical longevity.[56] Increasing the restoration thickness results in more curing light absorption and scattering and less light penetration within the material layers. Therefore, overall radiant exposure is reduced with increasing RBC thickness of more than 2 mm (Fig. 2B). As a consequence, the DC[57,58] and hardness[59,60] values of the material are also reduced. As a result, the RBC incremental layering technique is considered for cavities that exceed 2 mm in depth. This technique allows sufficient light exposure of the composite layers and lower polymerization shrinkage.[61,62]

Recently, manufacturers have introduced bulk-fill RBC that is marketed for placing and curing a single RBC increment with 4-10 mm thickness.[63] Many approaches were used to achieve adequate depth of cure in this class of material such as the use of specific polymerization modulators, increasing the translucency of the material, or by the use of potent initiator systems.[64] The bulk-fill RBC was found to achieve efficient polymerization reaction with an adequate degree of conversion and depth of cure.[65] More studies are needed to specify the factors that affect the radiant exposure of bulk-fill RBC and compare these factors to the ones that are associated with conventional RBCs.

Filler size/content

Different RBC compositions, filler size, weight, and volume have an impact on the ability for light to be transmitted throughout RBC layers.[66,67] A study[68] concluded that a lower filler-to-matrix ratio is associated with high DC. Another study[56] compared the DC of three different types of RBCs. They concluded that the DC depends significantly on the light penetration capacity through RBCs, which is affected by the filler-resin system. Low DC and microhardness result from the difference in the fillers' volume percentages in each type of the composites.[56] Large particles were found to have more DC as they are associated with a low filler-matrix interface which leads to higher exposure to the transmitted light.[69,70] However, large particles are associated with less wear resistance and less polymerization rate in the deep layer of the restoration.[71,72] On the other hand, small particles are associated with acceptable DC and more wear resistance despite the geometry of the particles.[71] Therefore, it is recommended to use an RBC that has nano-fillers in its composition. In addition, the DC decreases as the filler load increases. Mainly, this is because of the restriction of monomer mobility that limits the ability of the monomers to convert.[68,73]

Shades of the RBC

Different shades are available in the market with different translucencies, providing a wide range of selection for better shade matching with surrounding tooth structures, thus enhancing the esthetic of the RBC restorations.[54] For darker shades, some manufacturers have recommended increasing the exposure time. This evidence was supported as the shades have

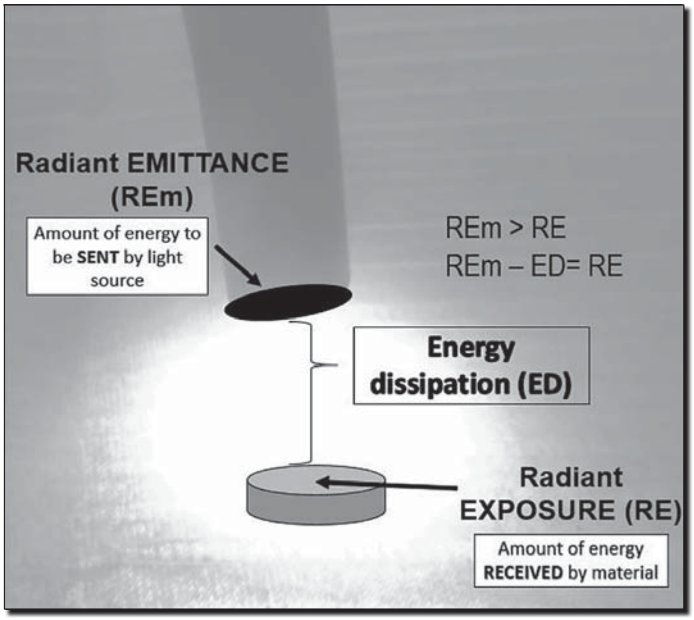

Fig. 3. Illustration highlighting the concepts of radiant emittance vs. radiant exposure (radiant received). Special attention to the energy dissipation that occurs in the space between the tip of LCU and the surface of the RBC.

an effect on the degree of monomer convergence.[74]

A study[75] evaluated the effect of four different shades on light reflection and absorbance, which were measured using a spectrophotometer. They found that the DC values were affected by the shade of RBCs. The effect of the RBC shade on the microhardness of the hybrid composite has also been addressed.[76] That study found that the A1 shade demonstrated higher microhardness values than the C2 shade. This could be a result of less light penetration through composites' more opaque shades.[76]

LIGHT CURING UNIT-RELATED FACTORS AFFECTING THE RADIANT EXPOSURE

The LCU is an essential part of the process of curing composites, and yet, the relevance of the LCU and how to use it properly to achieve the best outcome of RBCs is often underestimated.[77] Not all LCUs are similar in their features. They differ in several aspects including the amount of radiant emittance they generate to the restorative material, their tip configurations and the energy source to power the device. Figure 3 shows the concepts of radiant emittance vs. radiant exposure (radiance in J/cm^2), with special attention to the energy dissipation that occurs in the space between the tip of LCU and the surface of the RBC. Although the practitioner's goal is to place composite restorations in a time efficient manner, shorter time increments may not be the best choice depending on the LCU used.[78]

Types of LCU (LED and QTH)

The first introduced curing restorative materials used ultraviolet light polymerizing devices. These devices had short wavelengths of 10 nm to 380 nm, which led to a limited depth of cures. In the late 1970s, UV light was replaced by visible LCUs using a quartz-halogen bulb (QTH) producing wavelengths that range between 460 nm and 580 nm targeting the CQ present in the composite material.[79] These longer wavelengths allow for better penetration of the energy through the material. In the 1990s, the QTH improved, and the plasma arc curing units with a wavelength of 400 to 500 nm were introduced.[78] Later that year, the LED units were introduced providing light in the visible blue spectrum with a wavelength range of 450 to 490 nm. Because some RBCs have alternative photoinitiators that require a short wavelength (~410 nm),[80-83] a new LED unit, polywave, emitting multiple wavelengths was introduced to cure dental materials containing more than one photoinitiator with different light absorption spectra.[84,85]

QTH units deliver a broad emission spectrum but require an exposure time of between 30 and 60 seconds to adequately photo cure a 2 mm-thick increment of RBCs as a result of generating low radiant emittance. Several other disadvantages of the QTH LCU were reported including its use of electrical power to work and high operating temperature which limits the lifetime of the bulb.[86-88] Fans are associated with the QTH units to cool the device,[87] but they are noisy.[86] Moreover, conventional QTH LCUs cannot compete with LED LCUs because the emission spectrum of the QTH lamp emits a relatively broad visible light spectrum, which is not beneficial for photopolymerization and is scattered as heat.[89] Ceballos et al[57] found a higher DC using LED compared to other LCUs. LED LCU is considered as the gold standard to cure RBCs.[90,91]

Radiance emittance

The total radiant exposure (J/cm^2) is the result of radiance emittance (mW/cm^2) and exposure time (seconds). Increasing the total radiant emittance enhances the degree of cure and will improve the physical properties of RBCs.[90]

The total energy concept, which most of the literature agrees upon, states that the result of radiant emittance by exposure time should always result in the same radiant exposure. Thus, whether the radiant emittance is increased and the time is reduced, or the radiant emittance is decreased and the time is increased, the result should report the same total radiant exposure delivered to the restoration surface.[92,93] Dental materials textbooks state that a radiant exposure of 16 J/cm^2 should provide adequate polymerization of a 2 mm-thick increment of RBC.[94]

With the LCU's development, manufacturers produced increased radiant emittance units, which resulted in the ability to decrease the exposure time. More investigation is needed in this aspect as these modified LCUs may increase polymerization shrinkage and stress.[95]

Beam profile

The LCU was found to produce radiance emittance non-uniformity that resulted in a variation of the polymerization in the same surface of RBCs.[96-99] Studies[15,20,74,96,100,101] found that the radiant emittance and spectral emission were not uniform and negatively affected the polymerization of the restorations and their mechanical properties.[15-20] QTH LCU and plasma arc present more uniformity in their profiles because they have a broad spectral emission.[15,102] On the other hand, the off-center position of the LED chips may compromise the uniformity of the beam profile.[102] Price et al[96] conducted a study to evaluate the effect of distance on the beam uniformity and found that increasing the distance affected the polymerization, and the light output was not limited to a single value. Figure 4 shows the curing procedures in the clinical setting. Limits of the

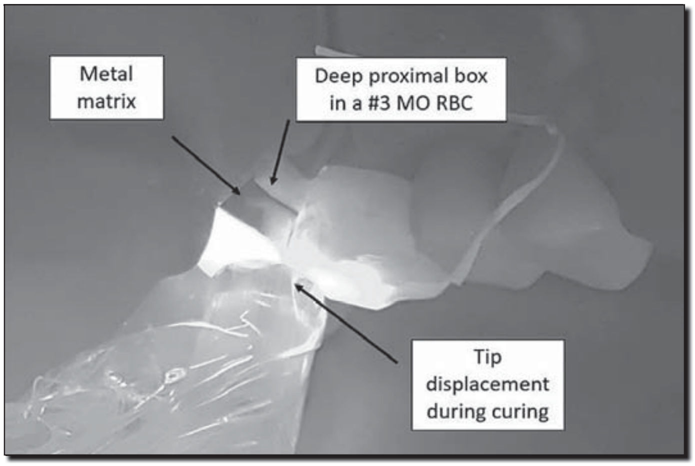

Fig. 4. View of the curing procedures in the clinical setting. Limitations of the mouth's opening, cavity depth, matrix band or interfering cusps are among the challenges to the delivery of radiant exposure during the light curing procedure.

Table 1. Recommended maintenance guidelines for the LCUs.

1. Before any clinical session, the LCU radiant emittance should be monitored using the built-in radiometer or any other radiometer suggested by the manufacturer.
2. If the LCU radiant emittance is low, it is recommended to increase the exposure time.
3. The LCU should frequently be cleaned; the infection control procedure should follow the manufacturer's guidelines to prevent any damage to the LCU.

mouth's opening, cavity depth, matrix band or interfering cusps are among challenges to the delivery of radiant exposure during the light curing procedure. Moreover, the beam non-uniformity is associated with a low microhardness of the RBCs,[18,100,103] higher light dispersion,[104] and low flexural strength.[105]

Maintenance

Dental LCUs should be monitored on a regular basis. It is recognized that the output from QTH units diminishes as the light source and filter age, and the output from LED units can also weaken with age or as a result of misuse.[100,106] Several studies that tested the LCUs in dental offices reported that many of these LCUs deliver less than 400 mW/cm^2, most likely due to inadequate maintenance.[99]

The introduction of higher power LCUs has not solved the problem of inadequate radiant emittance because many light guides on LCUs are either damaged or covered with resin contaminant.[85,107] Manufacturers have provided maintenance guidelines to ensure adequate production of radiant emittance by the LCUs (Table 1).

OPERATOR-RELATED FACTORS AFFECTING THE RADIANT EXPOSURE

Several operator-related factors, such as the polymerization time, the angulation of the LCU, and the distance between the surface of the RBC increment and the LCU's tip have a direct influence on the polymerization result and the DC.[108] Several studies[109,110] discussed the effect of the distance and the angulation on the amount of radiant emittance from different LCUs.

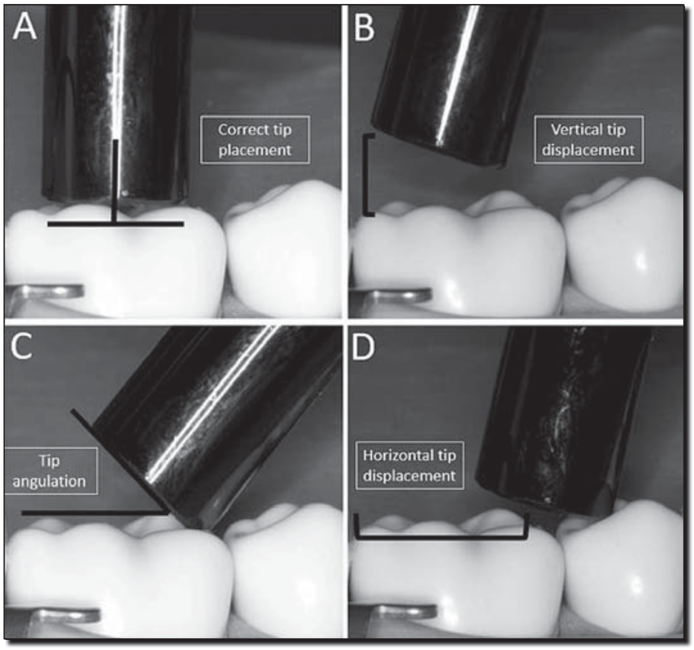

Fig. 5. **A.** The ideal position of the LCU's tip is to be as close as possible to the restoration surface. **B-D.** Tip placement during the light curing procedures that compromise the curing of the composite. **B.** The LCU's tip is located far away from the restoration surface. **C.** The LCU's tip is not placed perpendicular to the restoration surface. **D.** The LCU's tip is placed more mesially concerning the occlusal surface of the first molar.

LCU's tip angulation

Konerding et al[111] evaluated the radiant exposure transfer by different LCUs into a class III restoration as a function of tilt angle and distance, using a MARC Patient Simulator. They tested different angulations (0°, 5°, 10°, 15°, 20°) with three LCUs over a time interval of 20 seconds each. With all three LCUs, they observed an influence of the angulation on the radiant emittance delivered to the sensor confirming that the radiant emittance decreases when the angulation is increased, which reduces the radiant exposure. Figure 5 displays the ideal position and the most common scenarios of tip displacement and angulations performed by operators during light curing. Price et al[112] also stated that positioning the LCU's tip at 45° to the surface of the restoration would result in a 56% reduction in the radiant exposure received by the restoration. The influence of angulation on the radiant emittance could be explained by the fact that the light profile changes from circular to an ellipse when the LCU's tip is angulated, which affects the radiant emittance. Because of that, it is recommended to keep a 90° angle between the LCU's tip and RBCs.[113]

Distance and exposure time

A reduction in radiant emittance is observed as the distance between the LCU's tip and resin surface increases.[114-118] Some morphological features in the tooth structure may limit the radiant exposure and energy delivery to the RBCs as the distance between the cusp height or steepness and the cavity floor could reach 8 mm, which affect the radiant emittance reaching the restoration (Fig. 5).[119] Another example could be demonstrated in class II cavity preparation, where the gingival floor might be far away from the LCU's tip (Fig 4).[16] It was found that when the distance is increased from zero to 6 mm between the LCU and composites, the radiant emittance was

Table 2. Summary of the clinical guidelines to assure adequate light curing of resin composites.

1. Assure good isolation to prevent any leakage to the cavity.
2. Assure having the right thickness of resin composite (2 mm) as any thickness greater than 2 mm might affect the radiant exposure of the bottom of the placed restorations.
3. Eye protection before light curing is recommended to avoid any damage to the eye by the light.
4. Pre-heating resin composite before the placement is recommended to increase the DC%.
5. Minimize the distance as possible and avoid any inclination between the LCU's tip and composite surface to assure adequate amount of radiant exposure.
6. Stabilize the LCU's tip during light curing.
7. Locate the LCU's tip as close as possible to the restoration.
8. If there is any decrease in the radiant emittance or increase in the distance between the LCU's tip and resin composite, increase the exposure time to assure optimum polymerization.

reduced by 50%.[16] As a consequence, a lower DC will be expected when the radiant exposure is lower than that required for a proper polymerization, leading to several complications such as low microhardness, postoperative sensitivity, microleakage, and secondary caries (Fig. 1).[76,120,121]

Caldas et al[53] evaluated the influence of the distance on Knoop hardness using three different LCUs. They reported that increasing the distance leads to a decrease in RBC hardness, and they attributed this result to the lower DC due to reduced radiant emittance delivered to the composite.

Because of the influence of the distance, it was recommended[13] that a longer exposure time might be needed to deliver the required radiant exposure to the restoration when the distance to the resin increases. Studies[57,122] found that increasing the curing time by 10-20 seconds more than the manufacturer's recommendation resulted in higher DC and microhardness. Also, an inverse relationship was found between the radiant emittance level and the exposure time.[40] Table 2 summarizes the clinical guidelines to assure adequate light curing of resin composite by operators. These recommendations have considered the materials, curing unit and operators' factors.

Temperature

Increasing the temperature results in more monomer mobility, which could improve polymerization and increase the hardness of the material.[123,124] RBC stored at room temperature had an elevated DC (6-10%) when the temperature increased from 22°C to a mouth temperature of 35°C.[125] The same was noticed by Watts & Alnazzawi[126] who reported improved polymerization when the temperature was 37°C compared to 23°C. Accordingly, pre-heating the RBCs before the placement could be recommended to dental practitioners. However, any excessive rise of the temperature should be avoided to protect the pulp and the gingival tissues from injuries.[127]

Infection control

Several recommendations address the best practice of disinfecting LCU and its related materials. While light guides of most LCUs were designed to be removable for more convenient cleaning, autoclaving and disinfecting the light guides with a solution could affect the radiant emittance and the light transmission.[128,129] It is critical to follow the manufacturer's recommendations during infection control as many disinfectants compromise the components of LCU such as lenses, reflectors, and fiber optic light guide.[128-131] Disposable infection control barriers are used regularly as the most convenient method to prevent any kind of contamination during the dental visit, and also to avoid damaging the LCU by autoclaving or disinfecting. Compared to different types of barriers, the plastic wrap was the most effective barrier to be used without interfering with the radiant exposure of RBCs.[132,133] Using a single plastic wrap is highly susceptible to tearing during the dental visit, which could lead to contamination with saliva or blood. Some clinicians might be more comfortable using multiple layers of plastic wrap to assure avoiding such contamination. Using two barriers with a high radiant emittance LCU did not affect the hardness and the polymerization of RBCs.[134]

CONCLUSIONS

Although RBC restorations perform favorably in posterior and anterior teeth, their longevity and long-term survival rates were found to be correlated with several operator and material-related factors. Proper light-curing techniques were found to be one of the most important factors to achieve a sufficient degree of polymerization of these restorations and will decrease the number of underexposed resin-based restorations, improve their mechanical and physical properties and accordingly, increase their clinical longevity.

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