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Correlation between clinical performance and degree of conversion of resin cements: a literature review

Grace DE SOUZA[1], **Roberto Ruggiero BRAGA**[2], **Paulo Francisco CESAR**[2], **Guilherme Carpena LOPES**[3]

1- Faculty of Dentistry, University of Toronto, Toronto, ON, Canada.
2- Department of Biomaterials and Oral Biology, Faculty of Dentistry, University of São Paulo, São Paulo, SP, Brazil.
3- Faculty of Dentistry, Federal University of Santa Catarina, Florianópolis, SC, Brazil.

Corresponding address: Grace M. de Souza - 124 Edward Street, room #352 E. - Faculty of Dentistry, University of Toronto.
Toronto, ON – Canada - Postal code: M5G 1G6 - Phone: 416-9794934 - Ext. 4417 - Fax: 416-9794936 - e-mail: grace.desouza@dentistry.utoronto.ca

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ABSTRACT

Resin-based cements have been frequently employed in clinical practice to lute indirect restorations. However, there are numerous factors that may compromise the clinical performance of those cements. The aim of this literature review is to present and discuss some of the clinical factors that may affect the performance of current resin-based luting systems. Resin cements may have three different curing mechanisms: chemical curing, photo curing or a combination of both. Chemically cured systems are recommended to be used under opaque or thick restorations, due to the reduced access of the light. Photo-cured cements are mainly indicated for translucent veneers, due to the possibility of light transmission through the restoration. Dual-cured are more versatile systems and, theoretically, can be used in either situation, since the presence of both curing mechanisms might guarantee a high degree of conversion (DC) under every condition. However, it has been demonstrated that clinical procedures and characteristics of the materials may have many different implications in the DC of currently available resin cements, affecting their mechanical properties, bond strength to the substrate and the esthetic results of the restoration. Factors such as curing mechanism, choice of adhesive system, indirect restorative material and light-curing device may affect the degree of conversion of the cement and, therefore, have an effect on the clinical performance of resin-based cements. Specific measures are to be taken to ensure a higher DC of the luting system to be used.

Keywords: Dental prosthesis retention. Dental materials. Luting agents. Biocompatible materials.

INTRODUCTION

Resin cements are composite resins developed to deliver mechanical properties and handling characteristics that are important for luting indirect restorations. These cements contain different monomers, which are linked together during the polymerization reaction. Due to their application under an indirect restoration, in most cases the physical activation (photo activation) has very limited effect[14]. Therefore, there is a need for chemical activators. Activation of the polymerization means to induce the photo initiator (e.g., camphorquinone) or to break the molecule of the chemical initiator (benzoyl peroxide) so as to form free radicals that will initiate the polymerization. Free radicals link to monomers by breaking carbon-carbon double bonds. The continuous addition of monomers to a growing chain results in a polymeric chain. In general, the maximum degree of conversion (DC) – the percentage of aliphatic C=C (double) bonds converted into C-C (single) bonds to form the polymeric network – reached by resin cements is around 60%,[43] due to the increase of cement viscosity during the polymerization reaction, hindering the mobility of the reactive species[49]. The reaction slows down progressively up to a moment when new bonds cannot be made[71].

Resin cements have been frequently employed for bonding indirect restorations to the teeth due to their mechanical behavior[34] – superior to conventional cements (resin-free) –, possibility of adhesion to the restorative material[50] and to the tooth structure with[7] or without an adhesive system[60], and superior optical properties[36] when compared with conventional cements. However, limitations associated with the incomplete polymerization (low DC) of the cement may result in higher sorption and solubility values[67], causing faster degradation of the cement finish line by the acids present in the oral biofilm[67]. Degradation of resin-based cements reduces the bond strength between them and the substrate[39] and causes dissolution of the finish line at the restoration margin, which may mean the clinical loss of the restoration either by debonding, fracture or secondary caries[20]. Unreacted monomers (not bonded to the polymeric chain) may also irritate the pulp and generate a local inflammatory response[18].

There are multiple factors that may interfere with the DC of resin cements and, therefore, compromise the longevity of indirect restorations. Some of them are the material composition (monomers and other components of the activation system)[56], possible inadvertent interactions between the bonding system and the cement[63], characteristics of the restoration to be cemented (optical properties and thickness of the restoration)[14,15] and characteristics of the photo activation step[32]. This article aims to perform a comprehensive review of the factors involved in the DC of the resin-based luting systems and the impact of DC on luting system properties.

CURING MECHANISM

As previously mentioned, photo-activated or light-activated resin cements are indicated for situations where the light of the curing unit may pass through the restoration, such as translucent veneers and shallow inlays[56]. These cements are provided in a single paste with a photoinitiator system composed of a photosensitive component (usually camphorquinone) and a tertiary amine. The presence of light with a wavelength of 480 nm (blue region of the visible spectrum) activates camphorquinone[69], which binds to the tertiary amine and then releases two free radicals that will start the monomers conversion. Photo-cured resin cements have unlimited working time, with the polymerization starting right after the exposure of the material to light[4].

Chemically cured (self-cured) cements are indicated under thick restorations, for luting intrarradicular posts and crowns made of materials that block the light, such as metallic copings or highly opaque ceramics[42,68], aiming to guarantee maximum properties over time in areas that light energy is unable to reach[71]. The limitations of these systems are the reduced working time as opposed to the extended setting time[77] and the tendency to become "yellowish", due to the higher concentration of tertiary amines (activators)[29]. The polymerization reaction in self-cured cements requires the components of the activation system – tertiary amine and benzoyl peroxide – to get in contact by the mixing of two pastes, base and catalyst.

Dual-cure resin cements were developed in an attempt to combine the benefits of both photo and chemically activated systems[16,56,77], obtaining optimized DC in the deepest locations under a restoration, controlled working time and short setting time. In such systems, there is a catalyst paste with a chemical initiator, usually benzoyl peroxide, and a base paste containing the photo-cured resin cement and the tertiary amine responsible for the activation of the self-cure reaction[57]. When both pastes are mixed together and exposed to light, the polymerization happens by physical (photo) and chemical (redox) activation. The appropriate working time is controlled by inhibitors of the self-cure reaction or by the amount of activators of the polymerization[56]. It is expected that in areas where there is not enough light, the interaction between the tertiary amine and benzoyl peroxide will be enough to ensure the cement polymerization[4,57]. However, when not properly photo-activated, dual-cure resin cements may present reduced DC[47,49,77], which implicates in lower hardness[57], higher solubility[71], lower flexural[11,57] and compressive strengths, and lower bond strength to dentin in comparison to directly light-cured dual cements[7,77]. For instance, a self-adhesive dual cement applied in self-curing mode may show DC as low as 11% after a 10-minute setting time[77]. Considering the clinical application of the resin-based luting systems, which are used for the cementation of indirect restorations onto tooth structure, 10 min is an undesirably long time for a luting agent to obtain a great percentage of the optimal setting characteristics, without compromising the integrity of the margins and the cement layer under functional loading[8,77].

In general, light-cured and dual-cured cements activated by light through a restoration thinner than 2.0 mm[4,36,44,75] have higher DC than self-cured cements[77]. When a dual cement is self-cured (no activation by light), mechanical properties such as flexural strength, modulus and hardness are reduced by 68.9%, 59.2% and 91.1%, respectively, in comparison to original values presented by dual-cured samples[34]. There are different factors that may affect the DC of self-cured luting systems, such as the relatively high concentration of polymerization inhibitors used to extend the material's shelf life and to provide a clinically viable working time, ranging from 2 to 5 minutes, which adversely inhibits polymerization during the luting procedure[61]; the slow rate of polymerization activation and subsequent propagation of radicals in comparison to a directly light-activated material[6,49,51,61]; and the low concentration of benzoyl peroxide incorporated into those materials[6,49]. Furthermore, the hand-mixing of the two pastes incorporates air bubbles that further inhibit polymerization due to the presence of oxygen[79] and may act as stress concentrators that potentially result in cracking throughout the cement layer[56]. Although it has been demonstrated that the high incidence of air voids reduces the stress generated by the polymerization shrinkage of the cement due to a change in ratio of bonded to unbonded surfaces[5], the clinical benefits of the inclusion of pores have not been determined. Pores are also incorporated in dual-cured cements during mixing and they may become an esthetic concern when cementing veneers[16]. To minimize the undesired consequences of the hand-mixing procedure, some manufacturers provide cements in a self-mixing apparatus (Figure 1), which eliminates the manual mixing step, generates a homogeneous mix and reduces the incorporation of bubbles. However, voids have been observed after automatic mixing as well[56].

Interestingly, if light incidence on the cement layer is significantly compromised, the chemical activator of dual cements improves DC when compared to photo-activated-only systems[1,7,15,16] but the efficacy of the self-curing mode is still controversial[8,14,49] and varies from one material to another[44]. It has been demonstrated that the absence of the self-curing component in light-activated systems negatively affects the DC of these cements when the light-curing component is not able to guarantee an acceptable degree of conversion, for example when applied underneath onlays of greater thickness[1]. Considering a clinical application in which almost no light reaches the cement layer, it is desirable to use dual resin cements that present a chemical curing mechanism as efficient as photo-curing[8]. However, there is currently no resin luting system in the market capable of overcoming this limitation[2,7,45]. In general, the chemical activation of dual cements does not seem enough to compensate for the absence of light under thick or opaque restorations, even 24 hours after the beginning of the activation[1,15,32,61,64,65,75]. The DC of a self-adhesive dual cement may vary from 37% when light-cured for 20 seconds[77] to 58% when light-cured for 40 seconds[43], evidencing that there is also a direct correlation between light intensity received by a photo-activated material and its DC[14,46,49]. Laboratorial studies bring evidence that the activation time generally recommended by the manufacturer (Figure 1) is not sufficient to result in maximum degree of conversion[27,77]. Therefore, when highly opaque or thicker restorations need to be employed, a prolonged light exposure time is recommended (please read "Indirect Restorative Material" below), since a gradual increase in light-curing time and, therefore, in light transmission, gradually increases the Knoop hardness of resin-based luting systems[64]. Additionally, the use of a dual-cure system should always be considered to possibly increase the DC by means of a chemical activation of the monomeric system.

With regard to post-activation time, the 24-hour DC of light-cured and dual-cured cements is directly related to the DC obtained right after light exposure[4,75]. Even though DC is maximized during the first 30 minutes after light activation[2,79], some cements present gradual increase in DC for up to 24 hours, mainly when used in the dual-curing mode[4,10,28,31,64,79]. However, it has been speculated that a delay in light activation of dual-cured materials would enhance their properties[56] by allowing the self-polymerization promoters to react at some extent before being entrapped by the polymeric chains as soon as the photo-activation begins[49,74]. Delaying the light activation for 2 min may, for instance, compensate for a lower dose of light reaching the cement layer[49], but no effect is observed on the bond strength of resin cements to the substrate[28]. On the other hand, prolonged self-curing of the cement may also compromise the overall DC[49] and increase water sorption[71] when light activation is delayed for 10 min for the same reason, indicating that an ideal balance between self-curing and photo-activation is yet to be determined.

Under ideal circumstances, light-activated resin cements show higher DC than chemically cured resin cements, irrespective of brand names[49,57]. However, the DC of dual-cured cements is material-related, which means that it is more associated with the brand name than with the material classification *per se* and some systems are significantly more dependent on light activation than others[1,10,11,15,16,31,51,73,79]. Just as an illustration, the DC of a given dual-cured cement (RelyX ARC, 3M Espe, St. Paul, MN, USA) may vary from 81% to 61% when cured under light as opposed to total absence of light respectively, and from 56% to 26% when another dual-cured cement (RelyX Unicem, 3M Espe, St. Paul, MN, USA) is cured under the same conditions[43]. This difference may be explained by the difference in composition between both materials. For instance, some resin-based cements present twice as much benzoyl peroxide than others[51]. The lower DC may affect some critical properties of the resin-based cements[64]. Dual cements cured under a dual mode (photo+chemical) present lower toxicity and solubility than dual cements

Activation mode	Adhesive strategy	Brand name& Manufacturer	Commercial presentation	Recommended curing timeθ	Characteristics (Ref #)
DUAL-CURED	Self-adhesive	Biscem Bisco	Self-mixing applicator	20-30 s or 8 min*	DC of 41.5%[76] Higher DC (86%) with dual-curing mode and longer measuring time interval[2]
		Maxcem Elite Kerr	Self-mixing applicator	10-20 s on each surface or 4-5 min**	Low cytotoxicity[64] DC of 26.4%[76] Low bond strength (7.76 MPa) to Y-TZP[79] High shrinkage strain at different temperatures[39] Relatively high DC (68%) 10 min after light curing for 40 seconds[30]
		RelyX Unicem 3M ESPE	Capsules or self-mixing applicator	20 s on each surface or 5-6 min*	DC of 37.3%[76] Mild cytotoxicity[64] Good bond strength (21.1 MPa) to Y-TZP[79] Relatively high contraction stress and microhardness after light curing for 40 seconds[30] Low shrinkage strain at different temperatures[39] Low water solubility and high DC after 4-min curing delay[20]
		SmartCem 2 Dentsply Caulk	Self-mixing applicator	20-40 s on each surface or 6 min*	High water solubility and reduced DC after 4-min curing delay[20] Reasonable shrinkage strain at different temperatures[39]
		SpeedCem IvoclarVivadent	Self-mixing applicator	20 s on each surface or 160±40 s**	Reasonable shrinkage strain at different temperatures[39]
	Conventional	Clearfil Esthetic Cement Kuraray Inc.	Self-mixing applicator	20 s or 3 min*	Low bond strength (1.1 MPa) to superficial dentin[51]
		Duolink Bisco	Self-mixing applicator or two syringes	40 s on each surface or 3 min 30 s**	Relatively high contraction stress and microhardness after light curing for 40 seconds[30]
		Multilink Automix IvoclarVivadent	Self-mixing applicator	20 s on each surface or 180±30 s**	DC of 61.4%[76] Good bond strength (31.7 MPa) to Y-TZP[79] Low bond strength (3.1 MPa) to superficial dentin[51]
		Nexus Third Generation Kerr	Self-mixing applicator	20 s on each surface (no info available on self-curing)	Reasonable shrinkage strain at different temperatures[39] Very low bond strength to dentin under self-curing mode[44] High DC (84.8%) one week after light curing for 100 seconds[45]
		Panavia F 2.0 Kuraray Inc.	Two syringes	20 s on each surface or 3 min**	Inferior bond strength to resin composite (10.7 MPa) in different activation modes[27] DC (~78%) not influenced by the curing mode – self- or dual-curing –, but influenced by measuring time[2] Low bond strength (5.5 MPa) to superficial dentin[51] 8.1% of secondary caries under crowns after 5 years in clinical service[65] In combination with a modified crown design, provided the greatest fracture strength to an indirect restoration[66]
		RelyX ARC 3M ESPE	Self-mixing applicator	40 s at the margins or 10 min**	Fast curing and high DC[78] Superior bond strength to resin composite (16.5 MPa) in different activation modes and testing times[27] DC of 63% when light-cured under a 2 mm thick composite resin slab at room temperature[29] High water sorption and solubility[70]
		RelyX Ultimate 3M ESPE	Self-mixing applicator	20 s on each surface of 6 min*	Very low bond strength to dentin under self-curing mode[44] Relatively high DC (72%) one week after light curing for 100 seconds[45]
		Variolink II Ivoclar Vivadent	Two syringes	40 s on each surface (no info available on self-curing)	Relatively high cytotoxicity[64] Reasonable bond strength (15 MPa) to Y-TZP[79] DC of 56% when light-cured under a 2mm thick composite resin slab at room temperature[29] Low water sorption and solubility[70] High bond strength (14.6 MPa) to superficial dentin[51]
SELF-CURED	Convent.	C&B Cement Bisco	Self-mixing applicator or two syringes	4 ~ 7 min*	No measurable microhardness up to 10 min after mixing and low DC after 7 days[78]
		Panavia 21 Kuraray Inc.	Two pastes	~4 min 30 s*	Low cytotoxicity[64]
		Superbond C&B Sun Medical	Powder and liquid in different containers	7 min 30 s-9 min 30 s**	3.4% of secondary caries under crowns after 5 years in clinical service[65] High bond strength to both superficial (15.5 MPa) and deep (12.5 MPa) dentin[51]
LIGHT-CURED	Convent.	Choice 2 Bisco	One syringe	40 s over the veneer	~59% DC 7 days after light activation[78]
		RelyX Veneer 3M ESPE	One syringe	30 s on each surface	Reduced DC when 1.5 mm or thicker veneers are used[61]

&Brand names mentioned were reproduced from the research papers included in this literature review. Therefore, there may be other brand names currently in the market that would represent the categories of materials described in this Table. θLight-curing time recommended for QTH or LED curing devices. Dual and self-curing times may either consider room temperature (~23°C) or mouth temperature (~37°C). *Time after starting the mixture. **Time after placement of prostheses

DC=degree of conversion; LED=light-emitting diodes; QTH=Quartz-tungsten-halogen

Figure 1- Summary of some resin-based luting systems currently available and their characteristics based on the papers included in this review. Composition may vary significantly among different materials

cured under the self-curing mechanism (chemical only)[55,65]. Dual curing also leads to a rapid increase in hardness whereas chemically cured specimens are still soft 30 minutes[22] or even one hour[64] after mixing. Dual-curing mode also results in improved bond strength[44] and mechanical properties such as flexural strength, modulus and hardness, in comparison to light curing or chemical curing only[34,64].

Adhesive and self-adhesive resin cements have functional monomers such as 10-methacryloyloxydecyl dihidrogen phosphate (10-MDP), 4-methacryloxyethyl trimellitate anhydride (4-META) and phosphoric esters. These resin cements generally have a dual-cure mechanism. Self-adhesive cements have acidic functionalities in order to demineralize tooth structure[23], and an acid-base reaction between the acid groups of the monomers and the glass filler of the core material or the mineralized tooth surface starts immediately after the mixing of the components and application of the cement on the tooth surface[31]. However, those acidic monomers have been shown to negatively affect the cement degree of conversion, since they interfere with the amine initiator[77]. This interference compromises both the self-cure and the dual-cure modes[76]. The very low polymerization shrinkage strain of some self-adhesive cements may also be an evidence of reduced DC[40]. Indeed, there is a significant variation between the DC of different materials[31,40] and increasing the light-exposure from 20 s to 40 s does not improve DC values after 6 hours[31] as much as a temperature increase of the cement improves[40]. However, when the absence (self-cure) and the presence (dual-cure) of photo-activation are compared, the presence of light may result in a 10-fold increase in the material degree of conversion[40]. Although another initiator system based on sodium aryl sulfate or aryl-borate salts has been proposed[70] to compensate for the interaction between acidic monomers and the amine initiator in self-adhesive systems, no evidence has been found of any significant improvement in the DC for sodium persulfate-containing materials[8,77].

Another way to improve the polymerization kinetics of resin-based luting systems is to increase the temperature of the material[30,51]. High viscosity cements have significantly lower degree of conversion than low viscosity cements[24], probably due to the reduced mobility of the monomers in viscous materials. Increased temperature prior to and during polymerization leads to higher DC, due to increased free radical and monomer mobility[1,21] and collision frequency of the unreacted active groups resulting from the decrease in the viscosity of the material[21,30]. However, pre-heating (50°C) dual-cured resin cements with a higher concentration of the chemical activator (benzoyl peroxide) may result in significant decrease in working time, thus compromising the clinical application of the material[30,51], and still may not compensate for the absence of light[30]. The clinical applicability of the pre-heating technique is questionable, since the tooth structure could not be possibly heated up to 50°C, which would immediately result in the cement temperature decrease. Therefore, any evaluation on this topic should limit the pre-heating temperature to 37°C[51].

BONDING AND CEMENTATION

The bonding between resin cement and the tooth structure (or the core build-up material) is generally made possible by the use of a self-adhesive resin cement or by the application of a bonding agent/system. The bonding agent/system may either be self-etch or total-etch (etch-and-rinse)[13]. However, there are restrictions for the application of some simplified adhesive systems, more precisely two-step total-etch (primer and adhesive in one bottle) and "all-in-one" self-etch systems and resin cements with some chemical activation, either self-cured or dual-cured[37]. It has been shown that the lower the pH of the bonding agent employed, the lower the bond strength between self-cured cement and dentin[63]. The use of a simplified adhesive bonded to a self-cured cement results in 10-50% of the bond strength presented when the same adhesive is bonded to a light-cured cement[63].

The reason for those diminished bond strength values is that when simplified-step adhesives are used together with chemical-cured cements, there is an interaction between the residual acidic monomers from the adhesive inhibition layer and the binary peroxide-amine catalytic components that are commonly employed in chemically cured resin composites[63]. Therefore, the tertiary amine of the resin cement is neutralized and does not react with the initiator, resulting in low bond strength at the adhesive-cement interface[19]. Besides that, the adhesive layer of simplified systems (all-in-one) is highly permeable to dentinal fluids due to incomplete polymerization[12,13], and these are then kept at the interface between the adhesive and the cement, compromising the bonding between those two substrates[19,72], which is demonstrated by exclusively adhesive failure modes[63]. To maximize the performance of the resin cements, self-cured or dual-cure cements are to be employed only in association either with three-step total etch systems or with self-etching primer systems containing a separate bonding agent. For all of the other adhesive systems, the resin cement employed should be exclusively photo-activated.

INDIRECT RESTORATIVE MATERIAL

When photo-activation of a resin cement is performed, part of the visible light that reaches the crown is transmitted through the restoration, part is absorbed and part of it is reflected on the surface[57]. Consequently, the light intensity that effectively reaches the cement varies according to the optical characteristics of the restorative material[15,62], such as opacity[14,44] and shade[8,53], and the final thickness of the restoration[15,25,48]. The higher the thickness and the lower the value (darkness) of the restoration, the lower the light intensity reaching the cement layer, which may compromise the DC of a given cement[15,47,57,79].

There are many restorative systems nowadays that may be used for the manufacturing of all-ceramic crowns (Figure 2). Each one of these ceramic systems has a microstructure that directly interferes with the amount of light that may be transmitted through the restoration[14,78]. Considering restorations with similar shade and thickness, ceramics with a higher number of light scattering centers (interface between different microstructural phases) are more opaque and prone to block visible light[14,33,57,58], compromising the intensity of the physical polymerization of the resin cement[57]. Pores, frequently found in feldspathic porcelains and glass-infiltrated composites due to the processing method of these materials, act as light scattering centers as well. Light scattering occurs at interfaces of different phases with dissimilar refraction indexes. A free of pores porcelain would be a material with no light scattering interface and would thus show transmittance, resulting in high DC for dual cements even under a 3 mm-thick layer[15]. A multi-phase material would scatter the light because the incident light beam will change direction from one phase to another and the result will be a weaker incident light. A multi-phase structure within a material also results in light scattering and low transmittance[14]. Thereafter, glass-infiltrated alumina-zirconia (In-Ceram Zirconia System, Vita Zahnfabrik, Bad Säckingen, Baden-Württemberg, Germany) is the most opaque alternative among current clinical options, due to the presence of four distinct phases with different refraction indexes (alumina, Ceria-stabilized zirconia, lantanium glass and pores), with a final maximum transmittance of only 6% in 0.5 mm-thick copings, and when the thickness of the same material increases to 1.5 mm the transmittance becomes as low as 1% of the initial light intensity. Glass-infiltrated spinel ceramic (In-Ceram Spinell, Vita Zahnfabrik, Bad Säckingen, Baden-Württemberg, Germany) presents significantly higher transmittance because it has only two phases (glass and spinel), with similar refraction indexes.

When comparing the translucency of lithium-disilicate glass-ceramic and leucite-reinforced glass ceramic, Illie, et al.[36] (2008) observed that the first is more opaque than the latter (Figure 2). Lithium-disilicate glass ceramic contains a main crystalline phase of "elongated crystals building a scaffold of many small interlocking needle-like crystals randomly oriented"[36], with a second crystalline phase consisting of lithium orthophosphate[35]. On the other hand, leucite-reinforced glass-ceramic is a less dense material, characterized by the single crystal formation of leucite crystals[35,36], indicating that lithium-disilicate ceramics scatter more light than leucite ceramics. Light delivered to the cement layer through lithium-disilicate ceramic (shade medium opacity 1) is reduced to 45% under 1 mm ceramic slabs, 16% under 2 mm slabs and approximately 8% under 3 mm slabs[80]. Leucite-reinforced glass ceramic slabs reduce the light transmittance to 80%, 64% and 43% under 0.7, 1.4 and 2.0 mm thick samples, respectively[47].

As previously mentioned, the relationship between restoration thickness and transmittance is highly dependent on the opacity of the material[14,51,54,80]. However, the impact of the amount of light reaching the cement layer on its DC is controversial. Dual-cure resin cements activated by light under a 1.5 mm lithium-disilicate glass ceramic (Shade A2 low translucency) surface presented a DC similar to that of cements cured under direct light exposure[51], whilst samples cured through 1.4 mm-thick leucite-reinforced glass-ceramic slabs may[54] or may not[48] show significantly lower hardness values than groups activated with direct light exposure, depending on the luting system employed. In another study, samples light-cured under 1 or 2 mm thick lithium-disilicate slabs only showed decreased hardness when light exposure time was 20 s or less, indicating that longer exposure times may compensate for light attenuation of the indirect restorative material[80]. A randomized clinical split-mouth study evaluating the longevity of glass-infiltrated alumina crowns cemented with three different cements (two resin-based and one glass-ionomer) evidenced acceptable survival rates for all groups, with dual-cured cements showing higher survival rate than glass-ionomer cement, indicating that the opacity of the crown did not affect the performance of the cement/restoration[66]. It is important to remember that the final absolute transmittance values of a restoration would be even more compromised considering the thickness and the optical characteristics of the porcelain veneer layer[14]. The DC of a dual-cured cement activated under glass-infiltrated alumina (1.2 mm thickness) with porcelain veneer layer (0.8 mm thickness) is significantly reduced when compared to feldspathic porcelain samples (2 mm thick) and to the control

Material	Brand name& Manufacturer	Sample characteristics	Photo-curing conditions	Findings (Ref #)
Lithium disilicate glass ceramic	IPS e.max Press Ivoclar Vivadent	1.5 or 3.0 mm thick discs Shade A2 1.0, 2.0 or 3.0 mm thick discs Shade MO1 1.0 mm thick discs Shade A1 0.5 or 0.8 mm thick samples with veneer layer on top Shade LT, MO or HT	20 or 40 s at 600 mW/cm^2 10, 20, 30, 40, 50 or 60 s at 584 mW/cm^2 20 s at 1200 mW/cm^2 40 s at 1000 mW/cm^2	3 mm samples significantly reduced DC (52.9%) of Calibra at room temperature[50] Light intensity decreased ~ 62% under 1 mm, 86% under ~2 mm and 92% under ~3 mm thick samples. Light exposure of 30 s or longer may compensate for the 1 or 2 mm thick discs blocking the light[79] Final restoration color less influenced by cement shade, contrast ratio less affected when light-cured with 470 nm wavelength, no influence on mechanical properties of the resin cement underneath[51] The higher the opacity of the ceramic, the lower the DC of dual-cured cements; similar DC between 1.5 and 2.0 mm thick samples[13]
	IPS e.maxCAD Ivoclar Vivadent	0.5, 1.0, 2.0 or 3.0 mm discs Shade MO1 or MO4	5, 10 or 15 s at 1600 mW/cm^2	Reduced hardness with 1 mm or thicker samples, irrespective of the length of light exposure[35]
Leucite reinforced glass ceramic	IPS Empress Ivoclar Vivadent IPS Empress CAD Ivoclar Vivadent IPS Empress 2 Ivoclar Vivadent	1.0 mm thick discs Shade not informed 1.0 mm thick discs Shade A1 1.0, 1.5 or 2.0 mm thick discs Shade A2	10 s at 580~1650 mW/cm^2 20 s at 1200 mW/cm^2 60 s at 800 mW/cm^2	Light transmission reduced by ~55% through 1.0 mm thick samples[58] Final restoration color more influenced by cement shade, contrast ratio more affected when light-cured with 470 nm wavelength, no influence on mechanical properties of resin cement underneath[51] No effect of ceramic thickness on bond strength between substrate and resin cement[3]
	IPS Empress Esthetic Ivoclar Vivadent GN-I GC Corp. ProCAD Ivoclar Vivadent	0.7, 1.4 or 2 mm thick discs Shade A3 1.0, 2.0 or 3.0 mm thick discs Shade A3 0.5, 1.0, 2.0 or 3.0 mm discs Shade E100 or bleach	40 s at 605 mW/cm^2 3 cycles of 800 mW/cm^2 5, 10 or 15 s at 1600 mW/cm^2	Light intensity decreased ~20% under 0.7 mm, 36% under ~1.4 mm and 57% under ~2 mm thick samples. No significant differences observed in DC of resin cements[47] Negative correlation between cement hardness and ceramic thickness, with significant decrease starting from 1.0 mm thick samples[46] 15 seconds light exposure compensates for reduction in light transmittance in up to 2 mm thick samples[35]
Glass-infiltrated alumina composite	In-Ceram alumina Vita Zahnfabrick	0.5 or 0.8 mm thick sample with veneer layer on top Shade A2	40 s at 1000 mW/cm^2	Significantly decreased DC for both dual- (37~54%) and light-cured (24~30%) cements and both thicknesses[13]
Polycrystalline zirconia	ZR Ceramill Zi	0.5 or 0.8 mm thick sample with veneer layer on top Shade A2	40 s at 1000 mW/cm^2	Significantly decreased DC for both dual- (17~25%) and light-cured (22~24%) cements and both thicknesses[13]
Polycrystalline alumina	Procera Nobel Biocare	0.25 or 0.6 mm core thick discs with veneering material on top to equal 1.0 mm	10 s at 580~1650 mW/cm^2	Both core thicknesses blocked conventional halogen light completely; 0.25 mm core reduces Plasma Arc light by 66% and 0.6 mm by 79%[58]
Feldspathic porcelain	Ceramco II Dentsply Ceramco IPS InLine Ivoclar Vivadent Vita VM7 Vita Zahnfabrick	1.0 mm thick discs Shade not informed 1.5 or 2.0 mm thick discs Shade A2 2.0 mm thick discs Shade OM1, 2M2 or 5M3	10 s at 580~1650 mW/cm^2 40 s at 1000 mW/cm^2 20 or 40 at 900 mW/cm^2	Light transmission is reduced by ~63% through 1.0 mm thick samples[58] No significant reduction in DC, irrespective of sample thickness[13] The darkest shade significantly reduced DC of resin cements at both light activation times; when darker ceramic and darker resin cement are associated, 40 s light activation may significantly increase DC[52]
Micro-hybrid indirect resin composite	Sinfony 3M ESPE	1.5 mm thick discs Shade D A3	40 s at 800 mW/cm^2	DC of resin cements reduced from 1.5 up to 33% depending on the luting system used[72]
	Signum Heraus	2.0, 3.0 or 4.0 mm thick discs Shade A2	40 s at 1200 mW/cm^2 60 s at 800 mW/cm^2 120 s at 400 mW/cm^2	DC decreased ~21% for samples cured under 4 mm discs when compared to samples cured under 2 mm; no significant influence of the curing protocol on the DC[1]

&Brand names mentioned were reproduced from the research papers included in this literature review. Therefore, there may be other brand names currently in the market that would represent the categories of materials described in this Figure. DC=degree of conversion

Figure 2- Correlation between indirect restorative materials and the curing properties of the resin cement underneath

group, activated under direct light exposure[14].

When the impact of the shade of the ceramic system is evaluated, it can be observed that if shades with higher chroma are used, less energy reaches the cement layer, since dark pigments absorb a significant amount of light[9], negatively influencing the cure of light-dependant cements. Dual-cured cements light-activated under 2 mm-thick samples of darker dentin shade of feldspathic porcelain present significantly lower DC than cements light-activated under lighter shades[53]. When yellow and translucent shades of a resin cement were light-activated under the darker porcelain, only prolonged light-exposure time (40 seconds) was capable of increasing the DC of the cement yellow shade[53], indicating that the combination of darker shades in both the cement and the indirect restorative material compromise the overall DC of the cement layer.

With regard to laminate veneers, some studies show that although the bond strength between veneers and tooth structure is not affected by shade or opacity of the ceramic system, the DC of the cement may be diminished by either thicker, darker or more opaque restorations[15], frequently used to mask severely darkened teeth, and a lower DC of the cement layer may compromise the esthetic result due to the continuous discoloration of the material[75]. The analysis of the DC of a light-cured resin cement after the superimposition of different veneer materials with different thicknesses indicated that the effect of light attenuation on the degree of conversion is not significant only for ceramic thicknesses of 1.0 mm or less[62].

Considering the optical properties of the indirect restorative composites, there are different factors playing a role in light transmittance, such as particle size distribution, thickness of the restoration and shade. The smaller the particles, the more interfaces will be present acting as light scattering centers[33], consequently increasing the opacity of the material employed, which indicates that larger particles allow for deeper activation of the cement layer by light[4,57,58]. Interestingly, the hardness of dual resin-based cements is less affected when photo-activation is performed through an indirect restorative composite – either microfilled or micro-hybrid – than when it is performed through an all-ceramic system – lithium disilicate and glass ceramic[57]. When the effect of thickness is evaluated, there is indeed an inverse correlation between thickness of an indirect composite resin restoration and Knoop hardness of the resin based luting system[26]. Dual resin cements cured under 2 mm-thick micro-hybrid composite samples show significantly lower DC than samples cured under ideal conditions[30], and the DC of dual cements is 12% lower under 4 mm onlays in comparison to that measured under 2 mm thick onlays[1]. With regard to the effect of shade on indirect composite resin light transmittance, Arrais, et al.[8] (2008) demonstrated that only 11% of light reaches the cement layer when cured through a 2 mm microhybrid composite A2 shade as opposed to 8% when A4 shade was employed, but no effect on DC was observed for dual-cured resin cements with higher concentration of benzoyl peroxide. The authors pointed out that the adhesive component also presented a chemical activator of the polymerization and could, therefore, compensate for the absence of light[8].

LIGHT CURING DEVICE

It has been demonstrated that the hardness of dual-cured cements is dependent on the level of exposure to the curing light[32]. As previously mentioned, the component responsible for the chemical activation of the material cannot compensate for the total absence of light[3,32]. The higher the light intensity and the longer the exposure time of the resin cement, the higher the Knoop hardness of the dual-cured materials[64]. However, even when under direct light exposure, there is a limit above which the DC of a photo or dual-cure cement cannot be increased[44].

Quartz-tungsten-halogen (QTH) light curing units (LCU) deliver light irradiance varying between 400 and 1360 mW/cm^2 [17,50,64]. When exposure time (40 s, 60 s or 120 s) and intensity (1200, 800 or 400 mW/cm^2) of light exposure on DC of dual cements was evaluated, different materials showed different results[1], although all the associations resulted in the same amount of energy (48 J). Activation of dual cements under 2 mm resin composite onlays using low light intensity for prolonged time presented a trend towards higher DC, probably due to the slow increase in the material viscosity, allowing more monomers mobility[1].

Light-emitting diodes (LED)-based units were introduced in the market in 2001[76] and are another option to activate photo-cured resin cements. These units generate light under a narrower spectrum (between 450 and 490 nm) with the peak around 468 nm, the ideal wavelength for resin-based materials using camphorquinone as the photoinitiator[17]. When the photo-activation of a cement is performed through a ceramic system, light transmittance increases for higher wavelengths[57]. The higher mean wavelength of LED lights improves the capacity of the equipment to activate resin cements under indirect restorations[36,76]. However, light-intensity is also critical, since LED with relatively low light intensity (320 mW/cm^2) results in decreased Knoop hardness at the bottom of dual-cured cement samples[53].

The effect of QTH (905 mW/cm^2) and LED (1585 mW/cm^2) curing units on Knoop hardness of resin-based cements indicated that there was no effect of LCU on the hardness of dual-cure cements[54]. Samples cured under 1.4 and 2.0 mm ceramic slabs (leucite glass ceramic, shade A3) showed lower hardness values than samples cured under direct light exposure and under 0.7 mm slabs[54]. Authors observed that hardness on dual-cured luting agents may not be dependent on the light source, as long as the irradiance level for the effective wavelength region to activate the photo-initiator is similar[54].

With the application of high-power curing units in dentistry, LED-based equipment with high light intensity (1000-1600 mW/cm^2) are being advertised as an alternative to reduce the curing time of resin-based materials. However, the minimum time required to properly cure a dual-cured luting system is 15 s under ideal conditions, so that maximized mechanical properties can be obtained[36]. Therefore, it is not recommended to reduce the light exposure time to less than 15 seconds on each side of a restoration, irrespective of light intensity[36]. Indeed, it has been demonstrated that light-curing a dual-cure cement for 9 s with a LED device (1100 mW/cm^2) results in significantly reduced degree of conversion[41]. The authors observed that exposing dual-cure material to high intensity light may increase its viscosity more rapidly, hindering the migration of active radical components responsible for further polymerization[41]. Similar results were obtained when LED device (1100 mW/cm^2) with different activation modes and QTH (600 mW/cm^2) were used to photoactivate resin cements between ceramic samples (lithium disilicate) and human dentin, and the authors found out that groups photo-activated for 10 s presented inferior bond strength[50]. Higher bond strength results were obtained when LED devices under exponential mode and QTH were used, and since the exponential mode was applied for twice as much time as the other LED groups, the overall energy delivered was increased, which may have enhanced the DC[50]. Authors also observed that higher light intensity produces higher contraction strains during resin polymerization, which may promote debonding at the adhesive interface[50]. Therefore, prolonged exposure times are desirable not only to increase the energy delivered to the luting material, in an attempt to compensate for the attenuation of the light promoted by the indirect restorative material, but also to reduce stress generation at the cement-substrate interface, to ensure preservation of the bonding.

A comparison of different light curing equipment (QTH – 600 mW/cm^2; LED – 1400 mW/cm^2; argon ion laser – 600 mW/cm^2) used to activate resin cements under 2 mm-thick samples of composite resin indicated that the degree of conversion of the resin cements is again more related to the commercial brand and, consequently, to the material composition than to the curing device itself, with LED and argon ion laser devices resulting in lower DC for one of the materials in the photo-cured mode[69]. Although the short range of the spectra peak for LED devices may be advantageous when curing under ceramic systems, a wider range may be clinically interesting to photo-activate alternative photoinitiators, promoting a higher DC for QTH lights even in the presence of lower light intensity.

In addition to the factors presented above, there are other variables playing a role in the DC of light-activated resin-based cements, such as the distance between the tip of the curing device and the cement layer[4,52,75] and other indirect factors reducing the light intensity being delivered[38,50,52,59]. Based on the results presented and the number of studies indicating that prolonged light-activation may be beneficial for the DC of dual- or photo-cured cements[43,53,80], increasing the light exposure time, even though this would mean a couple more minutes of clinical procedure, would be certainly beneficial for the clinical performance of an indirect restoration.

CONCLUSION

The clinical success of an indirect restoration is not only attributed to the DC of the resin cement or to its mechanical properties, since there are other aspects that determine the clinical performance of dental prostheses. Nonetheless, ensuring a high DC is paramount to obtain the best out of the chemical and physical properties of the resin cement, besides being a critical factor for biocompatibility. When performing a luting procedure, one should pay attention to the characteristics of the indirect restorative material to be employed, and make a conscious decision of using a cement system that would be more indicated to the clinical case necessities. Curing modes and the best light-curing technique are examples of information that is to be available. It is crucial for clinicians to know and understand the cement systems they are working with.

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