Hardening of Dual-Cure Resin Cements and a Resin Composite Restorative Cured with QTH and LED Curing Units

(Durcissement des résines de cimentation à l'aide d'un double système de polymérisation et d'une résine composite de restauration polymérisable au QTH et au DEL)

• **Gildo Coelho Santos Jr**, DDS, MSc, PhD •
• **Omar El-Mowafy**, BDS, PhD, FADM •
• **Jose Henrique Rubo**, DDS, MSc, PhD •
• **Maria Jacinta Moreas Coelho Santos**, DDS, MSc, PhD •

Sommaire

Objectif : *Le but de cette étude était de déterminer les effets de l'intensité lumineuse et du type d'unité de polymérisation (à quartz-tungstène-halogène [QTH] ou à diode électroluminescente [DEL]) sur le durcissement de diverses résines-ciments et d'un matériau de restauration en résine composite.*

Méthodologie : *Les échantillons discaux ont été préparés à l'aide de 4 résines-ciments à double polymérisation (Variolink II, Calibra, Nexus 2 et RelyX ARC). Deux unités de photopolymérisation à QTH (Visilux 2, à 550 mW/cm^2 et Optilux 501 à 1360 mW/cm^2) et une unité de polymérisation à DEL (Elipar FreeLight, à 320 mW/cm^2) ont servi à la polymérisation. Les échantillons ont été photopolymérisés ou doublement polymérisés pendant 10, 30 ou 40 secondes avec 1 des 3 lampes (polymérisation appliquée seulement sur la surface supérieure) et ont été testés 24, heures après la polymérisation. D'autres échantillons de ciment ont été autopolymérisés et testés au bout de 15, 30 et 60 minutes et au bout de 24 heures. Le test consistait à mesurer l'indice de dureté de Knoop (IDK) pour chaque échantillon. Six valeurs IDK ont été obtenues seulement pour la surface supérieure des divers échantillons de ciments dans chaque groupe testé. Les échantillons discaux de 2,5 mm d'épaisseur ont aussi été préparés à partir d'un matériau de restauration en résine composite (XRV Herculite). Ils ont été photopolymérisés comme ci-dessus, et les mesures IDK ont été obtenues pour les surfaces supérieure et inférieure. On a déterminé la valeur IDK moyenne et appliqué une analyse de variance aux données.*

Résultats : *Les groupes ont été significativement différents ($p < 0,05$). La photopolymérisation à haute intensité a donné les valeurs IDK les plus élevées pour tous les matériaux avec l'un ou l'autre des 3 temps de photopolymérisation. Pour les ciments, la photopolymérisation à l'aide d'une lampe à DEL (en mode double polymérisation et en mode photopolymérisation) a abouti à des valeurs de dureté semblables à celles qu'on atteint avec la photopolymérisation traditionnelle avec une lampe à quartz-tungstène-halogène, même s'il y avait des exceptions. Toutefois, la polymérisation avec une lampe à DEL et la polymérisation avec une lampe traditionnelle à QTH ont toutes les 2 abouti à un durcissement moindre des surfaces inférieures des échantillons du matériau XRV Herculite pour les 3 temps de polymérisation. Pour tous les ciments, sauf Nexus 2, l'autopolymérisation à abouti à des valeurs de dureté significativement moins grandes que celles qui ont été obtenues avec la double polymérisation. Le mécanisme d'autopolymérisation du ciment Variolink II avait besoin de plus de temps pour s'activer que ceux des autres ciments.*

Conclusions : *La photopolymérisation à haute intensité et l'accroissement du temps de polymérisation ont donné les valeurs IDK les plus élevées. L'unité de polymérisation à DEL a été associée aux valeurs de dureté les plus basses pour les surfaces inférieures du matériau de restauration en résine composite.*

Mots clés MeSH : *composite resins/radiation effects; hardness; light; resin cements*

© J Can Dent Assoc 2004; 70(5):323–8
Cet article a été révisé par des pairs.

Resin cements have been used in dentistry for more than 3 decades. Their uses include cementation of orthodontic brackets, periodontal splints, resin-bonded fixed partial dentures, porcelain veneers, posts and nonmetallic inlays, onlays, crowns and fixed partial dentures. In addition, they can be useful in certain situations for enhancing retention of restorations and fixed partial dentures.[1,2] For cementation of nonmetallic inlays and onlays, dual-cured resin cements are typically used, as they afford better control during the cementation procedure and, in deep areas where the curing light cannot penetrate, the self-curing mechanism hardens the cement. However, a number of studies have indicated that the self-curing mechanism of some dual-cure cements is inadequate.[3–6] Other studies have reported an inverse relation between the thickness of ceramic inlays and the hardening of light-cured and dual-cured resin cements.[6–10] Furthermore, a study that investigated hardening of 3 dual-cured cements under resin composite inlays reported that with self-curing alone, hardening of the cements was insufficient when light was attenuated by tooth and restoration material.[11] Therefore, as newer versions of resin cements are introduced to the market, they must be examined to ensure that they meet the needs of dentists for their various applications.

Light curing of restorative resin composites and cements is accomplished with quartz-tungsten-halogen (QTH) light-curing units, plasma arc light-curing units or, more recently, light-emitting diode (LED) light-curing units. Although laser-based light-curing units were made available in the late 1980s they never gained popularity. Solid-state LEDs use junctions of doped semiconductors based on gallium nitride to directly emit light in the blue region of the spectrum, without the use of filters.[12] LED units have certain advantages over conventional light-curing units: many of them are wireless, and the LEDs have an estimated lifetime of about 10,000 hours (in contrast, QTH bulbs have a lifetime of 50 to 100 hours).[13,14] However, a number of newly introduced LED light-curing units have limited light output, and their effectiveness in curing resin composites and resin cement has not been fully investigated. Also, new versions of QTH light-curing units that provide high-intensity light (more than 800 mW/cm^2) have recently become available. Some of these units can emit light with an intensity greater than 1,300 mW/cm^2 if special turbo light guides are used.

The aim of this investigation was to evaluate the hardening of a group of dual-cure resin cements cured by conventional and high-intensity QTH and LED light-curing units. Also, the hardening of a resin composite restorative was investigated to ensure efficacy of a new LED light-curing unit.

Materials and Methods

Four dual-cure resin cements were examined in this study (**Table 1**). Disk specimens measuring 2.5 mm in thickness and 4 mm in diameter were prepared from each of these cements. For 3 of the cements, 3 sets of specimens were prepared: light-cured, dual-cured and self-cured; only dual-cured and self-cured specimens were prepared from RelyX Arc transparent cement (RLX). Three light-curing units were used, 2 based on QTH (Visilux 2, 3M/ESPE, St. Paul, Minn., with 550 mW/cm^2 intensity; Optilux 501, Kerr USA, Orange, Calif., with 1,360 mW/cm^2 intensity) and 1 based on LED (Elipar Freelight, 3M/ESPE, with 320 mW/cm^2 intensity). The LED light unit incorporates several LEDs, and light is emitted through a regular fibreoptic light guide. The light intensity of each curing unit was measured by means of a light meter (Optilux, model 100, Kerr USA). When dual-cured or self-cured specimens were prepared, the manufacturers' instructions for proportioning and mixing of the cement were followed. Steel rings were used for specimen preparation. For each specimen, a ring was placed on a glass section lined with a Mylar polyester strip, filled with the cement, and covered with another Mylar-lined glass section; the 2 glass sections were then pressed together with 2 clamps. Light curing was applied only to the upper surface of specimens, according to the group's test conditions. The surface of the light guide was placed directly in contact with the glass section covering the upper surface of the specimen. Light-cured and dual-cured specimens were subjected to light curing for 10, 30 or 40 seconds with 1 of the 3 light-curing units. Two specimens were prepared for each test condition. All specimens were stored dry in boxes in a darkened incubator at 37°C for 24 hours before testing.

Another set of specimens was prepared from the 4 cements according to the procedure described above but without light curing. The resulting specimens were stored as above and subjected to hardness testing at 15, 30 and 60 minutes and 24 hours after mixing.

A hardness tester with a Knoop indenter and 30-g weight (Tukon 300, Acco Industries Inc., Wilson Instrument Division, Bridgeport, Conn.) was used for testing the hardness of each specimen. Six readings were obtained from the upper surface only of each cement specimen in each test group. Mean Knoop hardness numbers (KHNs) were then calculated. Data were analyzed statistically with analysis of variance (ANOVA) andTukey's test.

To determine the efficacy of the 3 curing sources in hardening a resin composite restorative (XRV Herculite, shade A2, Kerr USA), specimens measuring 2.5 mm in thickness were

Table 1 **Specifications for resin cements evaluated in this study**

Brand name	Code	Manufacturer and location	Shade
Variolink II	VRK	Ivoclar/Vivadent, Liechtenstein	Transparent
Calibra	CLB	Dentsply/Caulk, Milford, Del.	Translucent
Nexus 2	NXS	Kerr USA, Orange, Calif.	Translucent
RelyX ARC	RLX	3M/ESPE, St. Paul, Minn.	A1-transparent

Table 2 Knoop hardness numbers for 3 cements subjected to light curing only

Intensity and curing time	Cement; mean Knoop hardness number ± SD		
	Variolink II transparent	Calibra translucent	Nexus 2 translucent
1,360 mW/cm²			
10 s	39.1 ± 3.4	5.1 ± 0.7	9.3 ± 0.4
30 s	46.0 ± 2.0	19.9 ± 1.9	27.6 ± 1.5
40 s	45.3 ± 1.5	34.4 ± 3.2	33.9 ± 3.6
550 mW/cm²			
10 s	30.6 ± 2.1	1.8 ± 0.3	6.0 ± 0.7
30 s	41.4 ± 1.6	8.8 ± 1.0	23.1 ± 2.8
40 s	48.3 ± 1.3	17.8 ± 0.8	26.5 ± 1.2
LED			
10 s	35.7 ± 0.7	3.7 ± 0.5	8.1 ± 1.1
30 s	36.2 ± 0.8	13.5 ± 0.5	19.9 ± 0.6
40 s	38.7 ± 2.4	20.6 ± 2.3	25.1 ± 1.4

SD = standard deviation.

Table 3 Knoop hardness numbers for 4 cements subjected to dual curing

Intensity and curing time	Cement; mean Knoop hardness number ± SD			
	Variolink II transparent	Calibra translucent	Nexus 2 translucent	RelyX ARC A1-transparent
1,360 mW/cm²				
10 s	51.6 ± 2.9	38.2 ± 1.5	40.9 ± 1.0	42.7 ± 3.8
30 s	52.9 ± 2.9	40.1 ± 1.9	46.6 ± 1.9	57.8 ± 2.8
40 s	58.6 ± 2.0	43.4 ± 1.9	52.0 ± 2.4	60.0 ± 2.4
550 mW/cm²				
10 s	39.8 ± 3.8	19.6 ± 1.4	24.7 ± 1.5	35.4 ± 2.0
30 s	44.4 ± 2.4	34.3 ± 1.4	44.7 ± 2.8	41.8 ± 1.5
40 s	50.5 ± 1.2	40.4 ± 2.7	46.8 ± 1.7	49.0 ± 3.6
LED				
10 s	48.3 ± 2.5	29.0 ± 2.5	29.1 ± 2.4	45.3 ± 2.3
30 s	48.3 ± 2.5	32.0 ± 2.7	34.1 ± 3.1	52.3 ± 1.7
40 s	49.0 ± 2.6	45.6 ± 1.0	43.0 ± 2.4	53.2 ± 2.7

SD = standard deviation.

prepared and light-cured (curing applied to upper surface only) for 10, 30 or 40 seconds with 1 of the 3 light-curing units. Both the upper and the lower surfaces of these specimens were subjected to Knoop hardness measurements (6 measurements for each surface under each test condition). Mean KHNs were calculated and the data analyzed with ANOVA.

Results

ANOVA indicated significant differences in mean KHN among the 3 cements that were subjected to light curing only (**Table 2**) ($p < 0.001$). For all 3 of these cements the KHN increased with increasing curing time (see **Figs. 1** to **3** at http://www.cda-adc.ca/jcda/vol-70/issue-5/323.html) and increasing light intensity. The mean KHN values for Variolink II cement (VRK) were significantly higher than those of the other 2 cements (Calibra [CLB], Nexus 2 [NXS]) under all test conditions (**Table 2**). In particular, the VRK cement achieved a greater degree of hardness with the shortest light-curing time than did the other 2 cements (**Fig. 1**), both of which needed more curing time to achieve a given level of hardness.

ANOVA revealed significant differences in mean KHN among the 4 cements when subjected to dual curing (**Table 3**) ($p < 0.001$). As with light curing, the hardness of all cements increased with increasing light-curing time (from 10 to 40 seconds; see **Figs. 4** to **6** at http://www.cda-adc.ca/jcda/vol-70/issue-5/323.html). After 10 seconds of curing, the hardness of the VRK cement was significantly higher than that of the other 3 cements, except for the RelyX Arc cement (RLX) with LED light curing (**Table 3**, **Fig. 4**). For all cements, the highest values of KHN at 10 seconds of curing were achieved with high-intensity light (1,360 mW/cm²) (**Table 3**, **Fig. 4**). After 30 seconds of curing the RLX cement had the highest values of KNH with both high-intensity and LED light curing but not with conventional light curing (550 mW/cm²) (**Table 3**, **Fig. 5**). For all cements, high-intensity light curing resulted in higher KHN values at both 10 and 40 seconds than was achieved with conventional

Table 4 Knoop hardness numbers for the 4 cements with self-curing only

	Cement; mean Knoop hardness number ± SD			
Time from mixing	Variolink II transparent	Calibra translucent	Nexus 2 translucent	RelyX ARC A1-transparent
15 min	–	12.1 ± 1.8	8.0 ± 0.5	3.2 ± 0.3
30 min	–	18.7 ± 2.6	8.9 ± 1.9	3.8 ± 0.2
60 min	–	26.7 ± 2.6	13.3 ± 0.9	4.3 ± 1.2
24 h	31.1 ± 2.1	35.4 ± 7.0	43.4 ± 1.3	25.3 ± 2.8

SD = standard deviation.

Table 5 Knoop hardness numbers for XRV Herculite A2 subjected to light curing

	Mean Knoop hardness number ± SD	
Intensity and curing time	Top surface	Bottom surface
1,360 mW/cm²		
10 s	61.9 ± 1.5	8.3 ± 0.4
30 s	65.8 ± 2.5	37.7 ± 1.3
40 s	70.2 ± 1.4	45.9 ± 2.3
550 mW/cm²		
10 s	48.6 ± 1.3	0.0
30 s	62.6 ± 1.7	16.0 ± 1.1
40 s	63.5 ± 1.6	25.4 ± 1.6
LED		
10 s	49.5 ± 2.5	0.0
30 s	53.2 ± 2.4	13.3 ± 0.3
40 s	60.8 ± 1.1	18.0 ± 1.4

SD = standard deviation.

and LED light curing (with the exception of the RLX cement at 10 seconds and CLB at 40 seconds) (**Table 3**).

ANOVA indicated significant differences in mean KHN among the 4 cements when subjected to self-curing only (**Table 4**) ($p < 0.001$). The VRK cement did not harden within the first hour after mixing (**Table 4**; see **Fig. 7** at http://www.cda-adc.ca/jcda/vol-70/issue-5/323.html). However, after 24 hours it had achieved a reasonable degree of hardness, and its hardness was greater than that of the RLX cement (**Fig.** 7). The CLB cement reached a degree of hardening after 15 minutes that was equivalent to a third of its hardness at 24 hour, whereas the NXS and RLX cements reached less that 20% of their 24-hour hardness after 15 minutes (**Table 4**, **Fig.** 7). At 24 hours the NXS cement had the highest mean KHN (**Table 4**).

Variability in light intensity had little effect on the upper surface of the XRV Herculite specimens but did have a significant effect on the lower surfaces (**Table 5**; see **Figs. 8** to **10** at http://www.cda-adc.ca/jcda/vol-70/issue-5/323.html). At 10 seconds, both conventional QTH and LED light curing failed to harden the lower surface of the specimens (**Fig. 8**). However, at 30 and 40 seconds some hardening took place (**Figs. 9** and **10**).

Discussion

The hardness of resinous materials measured at different stages of the polymerization reaction can be a useful indicator of the degree of monomer conversion. Typically, the harder the material becomes during polymerization, the greater the degree of monomer conversion. One study indicated a good correlation between KHN and degree of monomer conversion for 3 unfilled dental restorative resins.[15] Similar findings were reported in another study, in which 5 commercial resin composite materials were examined.[16] However, an absolute hardness number cannot be used to predict degree of monomer conversion in comparisons of different resinous materials.[15] Therefore, the findings of the study reported here can be considered reliable indicators of the degree of monomer conversion only for the materials examined. The authors of a study that investigated the degree of monomer conversion of 4 different resin cements found no evidence to indicate that the degree of monomer conversion for a chemically induced reaction was any greater at 24 hours after mixing than at 60 minutes.[17] That conclusion does not agree with the findings of the study reported here. In the current study, the hardness of 3 of the cements continued to increase from the time of mixing up to 24 hours after mixing when subjected to self-curing (**Table 4**). However, the degree of monomer conversion was not measured directly, and it is possible that variability in the formulations of the cements might be the reason for this difference between the 2 studies, given that different cements were investigated. The relatively small standard deviations reported in **Tables 2** to **4**, which did not exceed 10% of the means, indicate the reliability and appropriateness of the hardness test used and justify the number of KHN measurements that were obtained for each material under each test condition.

Compared with nonpolymeric cements, resin cement kits are more expensive, but in a dental office, it may be more economical to have a single resin cement kit that can be used for self-curing, dual curing or light curing. The VRK cement failed to harden in the self-curing mode within 1 hour after mixing and therefore should not be used with this method of curing. The other 3 cements had various hardening patterns. After 1 hour of self-curing, the CLB, NXS and RLX cements had mean KHN values of 26.7, 13.3 and 4.3, respectively (**Table 4**). These values represent 75.4%, 30.6% and 17.0%, respectively, of the hardness of these cements after 24 hours of self-curing (**Table 4**). Therefore, the CLB and NXS cements would perhaps be better candidates for use in the self-curing mode. These findings agree with previous reports that Nexus and Enforce cements (the original versions of the NXS and CLB cements used here) performed well in the self-curing mode.[6,18]

Nonetheless, mean KHN values for self-cured specimens at 24 hours were significantly lower than those obtained when specimens were dual cured for 40 seconds with high-intensity QTH light. This observation agrees with the findings of a recent study that determined the degree of curing of a group of orthodontic resin cements with infrared spectroscopic techniques.[19] The dual-cured cements demonstrated the highest degree of curing, whereas the self-cured ones had the lowest degree of curing.[19] In the current study, the mean KHN for CLB cement after 24 hours of self-curing was 81.6% of the value obtained with dual curing for 40 seconds with high-intensity light; the corresponding values for NXS and RLX cements were 83.5% and 42.2%, respectively. Also, the hardness values obtained with light curing only were lower than those obtained with dual curing. The mean KHN value for VRK cement after 40 seconds of high-intensity light curing was 77.3% of the corresponding value obtained with dual curing, whereas for the CLB and NXS cements, the percentages were 79.3% and 65.2%, respectively. Variability in the hardening patterns of the cements must be related to their chemical composition. The clinical significance of this finding is that dentists must be cautious about the potential for microleakage in the early hours after cementation of an indirect restoration with a resin cement when self-curing is used, if the self-curing reaction is slow or delayed. In the oral environment this may result in wash-out of the uncured cement with subsequent open margin, which could lead to postoperative sensitivity.

With the resin composite restorative, variability in light intensity had a detrimental effect on hardening of the lower surfaces of the specimens. Surprisingly, the new LED unit had the worst performance in this respect. Although 2.5 mm (the thickness of specimens in this study) might be at the upper limit of accepted thickness for a resin composite increment used for restoration, dentists do not have means to accurately determine the thickness of each resin composite increment they place into a prepared cavity. Thus, in large cavities in molars the thickness of a composite resin increment might reach this level. High-intensity QTH applied for an appropriate period of time is clearly a better option, as this curing mode will ensure sufficient hardening of the lower surface of thick increments and hence thorough polymerization.[20–22] Rueggeberg and others[22] indicated that the incremental layer thickness of composites should not exceed 2 mm, with 1 mm being ideal. They recommended exposure time of 60 seconds with a light intensity of at least 400 mW/cm^2; however, 40 seconds of exposure was deemed sufficient. Insufficient hardening of resin composite may result in postoperative sensitivity, as well as possible accelerated wear or degradation of the restoration in the oral environment.

Johnston and others,[23] who examined hardening of 2 light-activated products using 2.5 mm thick composite specimens, suggested that depth of polymerization may be based on a relative hardness value (hardness of lower surface/hardness of upper surface × 100) and, for practical purposes, suggested a ratio of 90%.[23] Yearn[24] used 80% relative hardness as a standard for adequate depth of polymerization. However, there is no internationally recognized standard for adequate depth of polymerization as measured by the relative hardness method. The authors of the current work suggest that 80% or higher relative hardness for composite specimens 2 mm thick should be used as a standard.

Conclusions

Within the limitations of the test conditions of this in vitro investigation the following conclusions can be reached:

1. High-intensity light curing resulted in a consistently greater degree of hardness for all resin-based materials tested at the 3 curing times.
2. With some exceptions, LED light curing resulted in hardness of upper surfaces of cement specimens similar to that achieved with conventional QTH light curing.
3. For all cements except NXS, self-curing resulted in significantly lower hardness values than dual curing.
4. The self-curing mechanism of VRK cement needed more time to activate than the mechanisms of the other cements.
5. LED light curing resulted in the lowest KHN values on the lower surfaces of the composite restorative specimens. ❖

Remerciements : *Les auteurs souhaitent remercier CAPES (Brésil) pour avoir appuyé en partie l'étude et 3M/ESPE Canada, Dentsply Canada et Kerr/USA pour avoir fourni les résines-ciments.*

*Le **Dr Coelho Santos Jr.** est professeur agrégé, Département de dentisterie opératoire, Université de Bahia, Faculté de médecine dentaire, Salvador, BA, Brésil.*

*Le **Dr El-Mowafy** est professeur agrégé de dentisterie restauratrice, Département des sciences cliniques, Université de Toronto (Ontario).*

*Le **Dr Rubo** est professeur agrégé, Département de prosthodontie, École Bauru de médecine dentaire, Université de São Paulo, SP, Brésil.*

*La **Dre Moreas Coelho Santos** est professeure agrégée, Département de dentisterie opératoire, Université de Bahia, Faculté de médecine dentaire, Salvador, BA, Brésil.*

Écrire au : *Dr Omar El-Mowafy, Département des sciences cliniques, Faculté de médecine dentaire, Université de Toronto, 124, rue Edward, Toronto ON M5G 1G6. Courriel : oel.mowafy@utoronto.ca.*

Les auteurs n'ont aucun intérêt financier déclaré dans la ou les sociétés qui fabriquent les produits mentionnés dans cet article.

Références

1. El-Mowafy OM. The use of resin cements in restorative dentistry to overcome retention problems. *J Can Dent Assoc* 2001; 67(2):97–102.

2. El-Mowafy OM, Fenton AH, Forrester N, Milenkovic M. Retention of metal ceramic crowns cemented with resin cements: effects of preparation taper and height. *J Prosthet Dent* 1996; 76(5):524–9.

3. Darr AH, Jacobson PH. Conversion of dual cure luting cements. *J Oral Rehabil* 1995; 22(1):43–7.

4. El-Badrawy WA, El-Mowafy OM. Chemical versus dual curing of resin inlay cements. *J Prosthet Dent* 1995; 73(6):515–24.

5. Linden JJ, Swift EJ, Boyer DB, Davis BK. Photo-activation of resin cements through porcelain veneers. *J Dent Res* 1991; 70(2):154–7.

6. El-Mowafy OM, Rubo MH, El-Badrawy WA. Hardening of new resin cements cured through a ceramic inlay. *Oper Dent* 1999; 24(1):38–44.

7. Blackman R, Barghi N, Duke E. Influence of ceramic thickness on the polymerization of light-cured resin cement. *J Prosthet Dent* 1990; 63(3):295–300.

8. Chan KC, Boyer DB. Curing light-activated composite cement through porcelain. *J Dent Res* 1989; 68(3):476–80.

9. Uctasli S, Hasanreisoglu U, Wilson HJ. The attenuation of radiation by porcelain and its effect on polymerization of resin cements. *J Oral Rehabil* 1994; 21(5):565–75.

10. Hofmann N, Papsthart G, Hugo B, Klaiber B. Comparison of photo-activation versus chemical or dual-curing of resin-based luting cements regarding flexural strength, modulus of elasticity and surface hardness. *J Oral Rehabil* 2001; 28(11):1022–8.

11. Hasegawa EA, Boyer DB, Chan DC. Hardening of dual-cured cements under composite resin inlays. *J Prosthet Dent* 1991; 66(2):187–92.

12. Craig RG, Powers JM, editors. Restorative dental materials. 11th ed. St. Louis: Mosby; 2002. p. 251.

13. Dunn WJ, Bush AC. A comparison of polymerization by light-emitting diode and halogen-based light-curing units. *J Am Dent Assoc* 2002; 133(3):335–41.

14. Mills RW, Jandt KD, Ashworth SH. Dental composite depth of cure with halogen and blue light emitting diode technology. *Brit Dent J* 1999; 186(8):388–91.

15. Ferracane JL. Correlation between hardness and degree of conversion during the setting reaction of unfilled dental restorative resins. *Dent Mater* 1985; 1(1):11–4.

16. Eliades GC, Vougiouklakis GJ, Caputo AA. Degree of conversion in light-cured composites. *Dent Mater* 1987; 3(1):19–25.

17. Ruggeberg FA, Caughman WF. The influence of light exposure on polymerization of dual-cure resin cements. *Oper Dent* 1993; 18(2):48–55.

18. El-Mowafy OM, Rubo MH. Influence of composite inlay/onlay thickness on hardening of dual-cured resin cements. *J Can Dent Assoc* 2000; 66:147. Available from: URL: www.cda-adc.ca/jcda/vol-66/issue-3/147.pdf.

19. Eliades T, Eliades G, Bradley TG, Watts DC. Degree of cure of orthodontic adhesives with various polymerization initiation modes. *Eur J Orthod* 2000; 22(4):395–9.

20. Price RB, Derand T, Loney RW, Andreou P. Effect of light source and specimen thickness on the surface hardness of resin composite. *Am J Dent* 2002; 15(1):47–53.

21. Rueggeberg FA, Caughman WF, Curtis Jr JW, Davis HC. Factors affecting cure at depths within light-activated resin composites. *Am J Dent* 1993; 6(2):91–5.

22. Rueggeberg FA, Caughman WF, Curtis Jr JW. Effect of light intensity and exposure duration on cure of resin composites. *Oper Dent* 1994; 19(1):26–32.

23. Johnston WM, Leung RL, Fan PL. A mathematical model for post-irradiation hardening of photoactivated composite resins. *Dent Mater* 1985; 1(5):191–4.

24. Yearn JA. Factors affecting cure of visible light activated composites. *Int Dent J* 1985; 35(3):218–25.

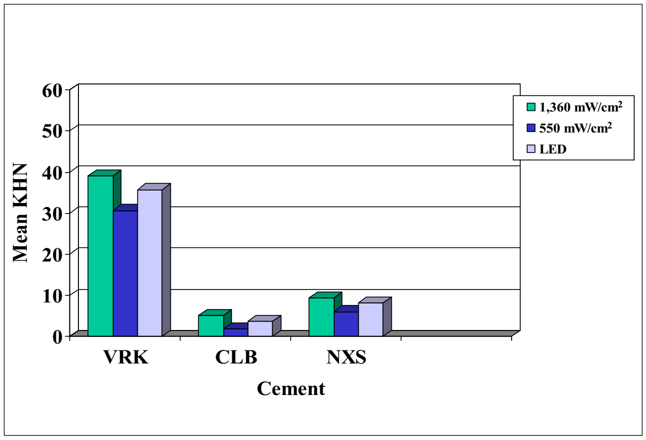

Figure 1: *Mean hardness of dual-cured resin cements subjected to light curing only for 10 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2.*

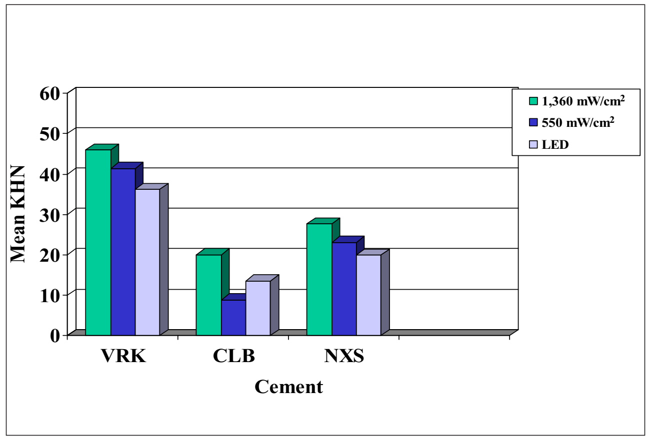

Figure 2: *Mean hardness of dual-cured resin cements subjected to light curing only for 30 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2.*

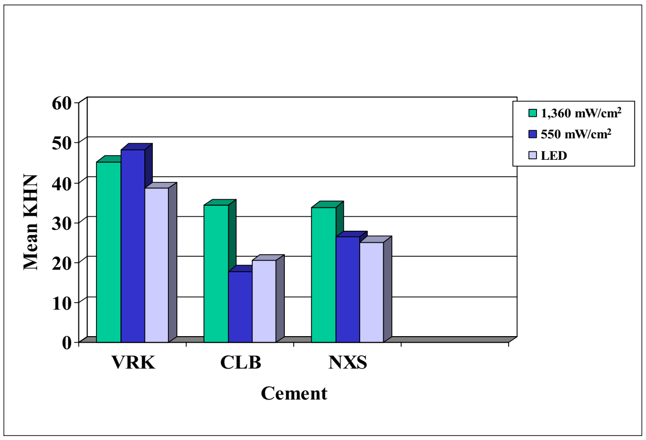

Figure 3: *Mean hardness of dual-cured resin cements subjected to light curing only for 40 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2.*

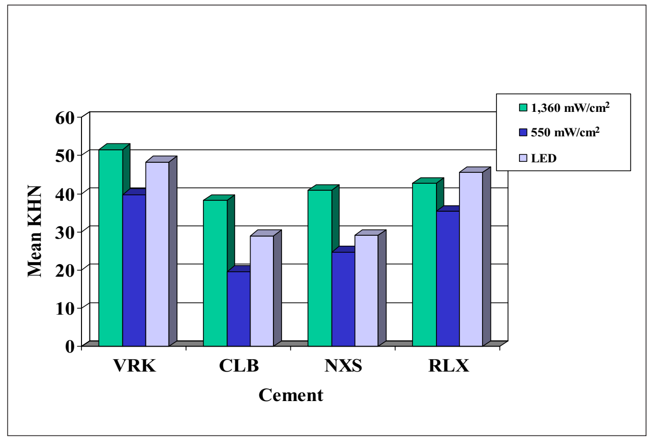

Figure 4: *Mean hardness of dual-cured resin cements subjected to dual curing for 10 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2, RLX = RelyX Arc.*

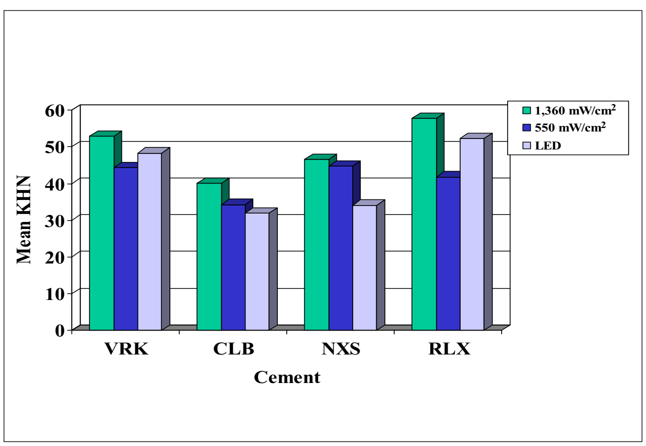

Figure 5: *Mean hardness of dual-cured resin cements subjected to dual curing for 30 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2, RLX = RelyX Arc.*

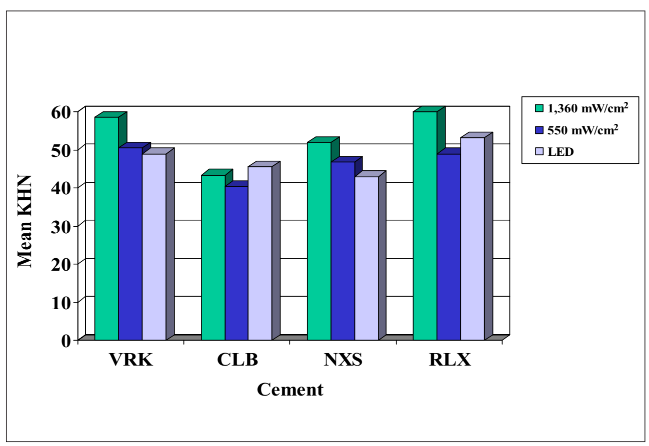

Figure 6: *Mean hardness of dual-cured resin cements subjected to dual curing for 40 seconds. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2, RLX = RelyX Arc.*

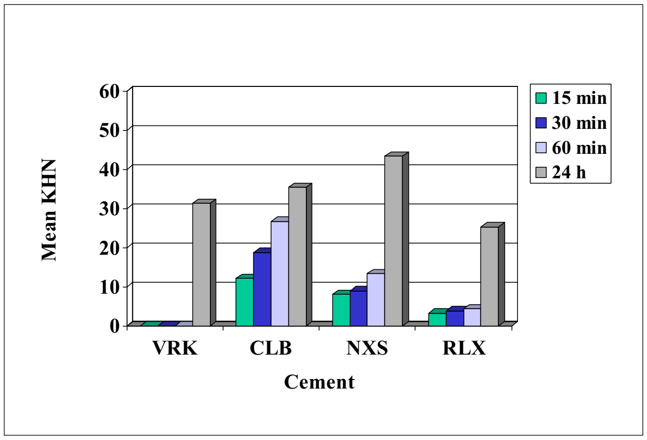

Figure 7: *Mean hardness of dual-cured resin cements with self-curing only. KHN = Knoop hardness number, VRK = Variolink II, CLB = Calibra, NXS = Nexus 2, RLX = RelyX Arc.*

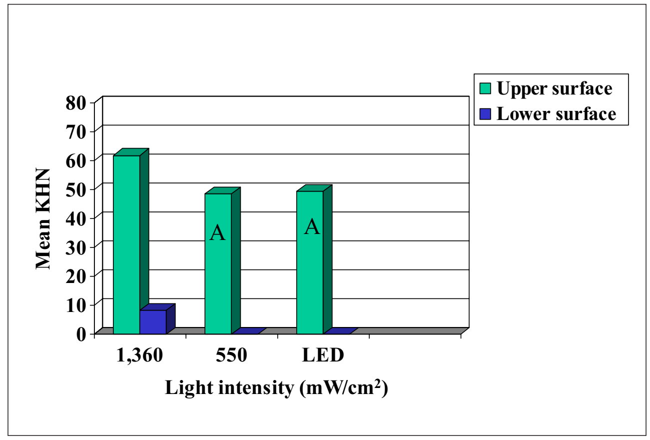

Figure 8: *Mean hardness of XRV Herculite A2 restorative subjected to light curing for 10 seconds. KHN = Knoop hardness number.*
A = Means are not significantly different.

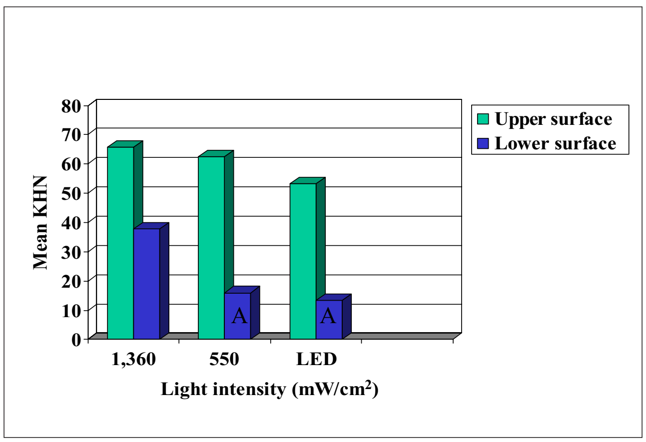

Figure 9: *Mean hardness of XRV Herculite A2 restorative subjected to light curing for 30 seconds. KHN = Knoop hardness number.*
A = Means are not significantly different.

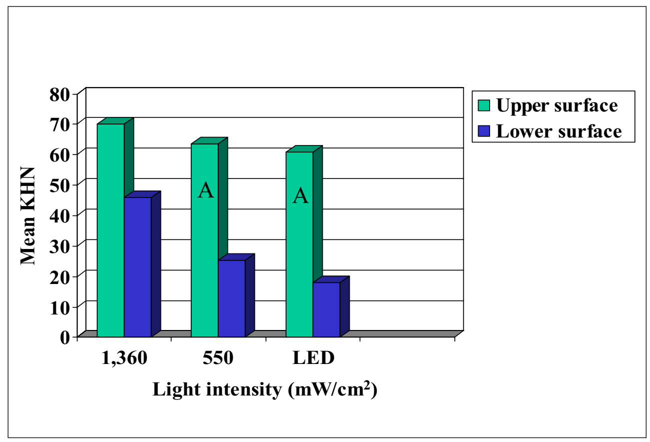

Figure 10: *Mean hardness of XRV Herculite A2 restorative subjected to light curing for 40 seconds. KHN = Knoop hardness number.*
A = Means are not significantly different.