Comparison of Quartz-Tungsten-Halogen, Light-emitting Diode, and Plasma Arc Curing Lights

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Purpose: This study determined which light source was best at photopolymerizing five representative brands of resin composite. The hypothesis was that there would be no difference in the hardness of the composites when irradiated by any of the lights.

Materials and Methods: Six curing light/tip combinations were used to photopolymerize five resin composites. In accordance with the manufacturer's instructions, the PAC light was used for 3 s and the high intensity QTH light was used for 5 s. The other QTH and LED lights were used for 40 s. To represent the clinical environment, the samples were irradiated at a distance of 2 and 9 mm away from the tip of the light guide. The Knoop hardness was measured at the top and bottom of the composites after 15 min and again at 24 h. The hardness data were compared using a general linear model analysis with Sidak's adjustment for multiple comparisons with $p < 0.01$ as the level of significance.

Results: The 6 curing light/tip combinations had different effects on the hardness of the 5 composites ($p < 0.01$). The two LED lights could not cure the neutral shade of Pyramid Enamel in 40 s. As the distance increased from 2 to 9 mm, the decrease in hardness was not similar amongst the different light/tips and composite combinations ($p < 0.0012$). The curing light/tip combination which delivered the greatest total energy produced the hardest specimens.

Conclusion: 1) The 6 curing light/tip combinations had different effects on the hardness of the 5 composites ($p < 0.01$). 2) Neither of the two LED lights used was able to adequately polymerize the five resin composites tested. 3) The QTH light, which delivered the greatest total energy, always produced the hardest resin composite. 4) When the distance of the composites from the light guides was increased, the effect on their hardness was not the same for all light/tip combinations. It is therefore not possible to predict the performance of a curing light at 9 mm based upon power density measurements or hardness data recorded when the tip of the light guide is 2 mm away.

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Dentists have a choice of various types of curing lights when photopolymerizing resin composites: conventional quartz-tungsten-halogen (QTH), light-emitting diode (LED), plasma arc (PAC), or laser curing lights. These lights have different characteristics and claimed advantages, but the most favourable irradiation procedure for photocuring resin composite restorations has not yet been determined.[45]

White light contains a spectrum of wavelengths. The photoinitiators used in dental resins are commonly activated by blue light in the wavelengths between 400 and 515 nm.[11,20,45] In the dental office, this blue light is usually generated by a light-curing unit (LCU) with a quartz-tungsten-halogen (QTH) bulb. The QTH light bulb produces a broad spectrum of wavelengths, and a filter located inside the LCU removes most of the wavelengths which are not useful when curing dental resins.[2,45] Conversely, LCUs which use LEDs or a laser produce a narrower range of wavelengths which have been chosen to match the photoinitiator in the resin.

When light energy is used to polymerize a resin, photons hit the photoinitiator molecules (eg, camphorquinone) which are then activated and raised to the "triplet" or excited state. If in this excited state the photoinitiator collides with an amine, a free radical is formed. This free radical can then interact with the carbon-carbon double bond (C=C) of a monomer molecule and initiate polymerization.[45]

The power density from a LCU, also referred to as light intensity, is the number of photons per second (Watts) emitted by a light source per unit area (W/cm^2).[6,11] The energy density (Joules/cm^2) emitted by the light source is calculated by multiplying the power density by the total exposure time.[6,11] It has been reported that a QTH light should deliver a minimum power density of 300 to 400 mW/cm^2 to adequately cure a 1.5 to 2 mm increment of resin composite in the manufacturers' recommended curing time, which is usually 40 s.[20,46,53] After 40 s at 300 mW/cm^2 the resin composite will have received 12 J/cm^2. This may be sufficient energy density for adequate polymerization to occur,[20] but others have recommended that a 2-mm-thick increment of resin composite should receive between 16 to 24 J/cm^2 to be adequately polymerized.[9,46]

If the restoration does not receive sufficient total energy at the correct wavelengths, the degree of conversion will be inadequate.[31,46,47] Consequently, there may be increased cytotoxicity,[7,8] reduced ultimate hardness,[3,9,14,19] decreased dynamic elastic modulus,[25] breakdown at the margins of the restoration,[22] increased wear and a weak bond between the tooth and the resin composite restoration.[27] Atmospheric oxygen inhibits the polymerization at the surface of light-activated resin composites. This air-inhibited layer is usually cured when the composite covering the bonding system is irradiated. If insufficient light energy passes through the resin composite, this air-inhibited layer on the surface of the bonding agent may not polymerize resulting in a weak bond between the tooth and the resin composite.

Manufacturers have increased the power density from their light sources to reduce exposure time and speed up dental treatment.[15,16,34,45,51] One method to increase the power density uses a higher power QTH light bulb. The Phase II light (Den-Mat, Santa Maria, CA, USA) uses a 250-W bulb as compared to an 80-W bulb in the Optilux 501 (SDS Kerr, Danbury, CT, USA). Den-Mat claims that 5 s of irradiation with their high-intensity QTH Phase II light provides the same polymerization as 30 to 40 s irradiation using a conventional curing light.[16] The power density can also be increased if a turbo light guide is used. The increased power density from turbo light guides has been reported to increase both the degree of conversion and the hardness of resin composites.[12,40]

An alternative method to increase the power density uses a high intensity PAC light source. Light is produced between two electrodes surrounded by electrically conductive gas (xenon) inside the LCU. When a high voltage is applied, a broad-spectrum arc of light is generated which is then filtered to obtain the wavelengths of blue light needed to polymerize dental resins.[11] One manufacturer has claimed that in 3 s, its light provides polymerization equivalent to 30 to 40 s of irradiation using a conventional QTH curing light.[15] Another manufacturer claimed that 3 s of curing with its PAC light is equivalent to 45 s of irradiation using a conventional QTH source with a power density $\geq$ 500 mW/cm^2.[1] Although shorter curing times may be a feature desired by many dentists, the effects of faster curing with high power densities on the resin composite remain controversial.[4,5,26,30,35,40,52,59] Inadequate polymerization and increased microleakage along the dentin margins have been reported when using PAC lights.[4,5,33,35,40,52,59]

Light emitting diodes (LED) convert electricity into light more efficiently, thereby producing less heat. LED technology eliminates the need for filters and may reduce heat generation to the extent that cooling fans may not be required or need only be of low capacity. Consequently, LED curing lights can operate on battery-power, so providing the dentist with a portable, silent and cordless LCU, which should function much longer than the alternatives. LED technology is therefore considered very promising for use in LCUs.[2,10,13,32] Dental resins irradiated using blue light LEDs have been reported to have a higher degree of polymerization and more stable three-dimensional structures than those cured with QTH lights.[32] It has also been reported that one LED

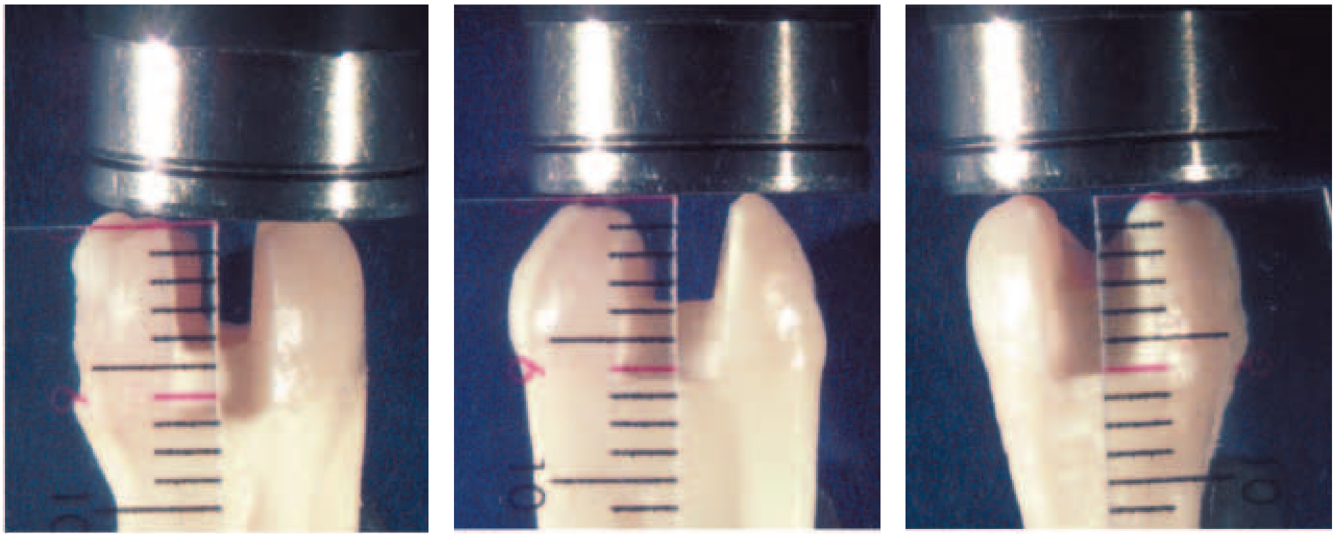

Fig 1 Three tooth preparations extending just past the cementoenamel junction showing a preparation floor-to-light-guide distance of (left to right) 6.9 mm, 6.5 mm, and 6.2 mm.

light cured three dental composites to a significantly greater depth than a QTH LCU.[29] However, another study reported that the Knoop hardness values of two resin composites were lower when irradiated using LED curing lights compared to when they were irradiated using QTH curing lights.[18]

The amount of light energy received at the top and bottom of a restoration may differ considerably and is affected by many variables, such as design and size of the light guide, distance of the light guide tip from the resin composite, power density, exposure duration, increment thickness, material composition, and shade and opacity of the resin composite.[3,12,23,25,28,47,49,56,61,64] Consequently, the hardness at the top of the restoration is a poor predictor of the hardness of the resin at the bottom of the restoration.[37,38,40,46,47] Therefore, to compare the curing abilities of different lights, the hardness should be measured at the bottom of a clinically relevant thickness of composite.

Clinically, it is not always possible to position the tip of the light guide adjacent to the surface of the resin (Fig 1), and consequently less light energy reaches the resin than is recorded at the tip of the light guide.[31,38,39,41,49,54] A 6-mm space between a standard light guide and the radiometer will reduce the power density by approximately 50%.[38,41] Therefore, the 6- to 7-mm distance often encountered between the light guide and the floor of the restoration (Fig 1) will have a considerable effect on the amount of energy received by the resin or dental bonding system (DBS) at the floor of the proximal box in a molar.[38,39,41,64]

Not all light guides focus the light from the LCU in the same way, and the relationship between power density and distance is influenced by the design of the guide.[24,41,54] Although the turbo light guide is known to boost the power density at the tip of the light guide,[12,41] light has been shown to diffuse more rapidly from the tip of the turbo guide. Beyond 5 mm, a standard light guide may provide a greater power density than a turbo light guide.[41] Therefore, power measurements made with the tip of the light guide in contact with the radiometer may be misleading, and any comparison of dental curing lights should be made with the tip of the light guide at clinically relevant distances from the radiometer.

The purpose of this study was to test QTH, LED, and PAC light sources which represent curing lights commonly used in North America to determine which light was best at photopolymerizing several representative resin composites. Knoop hardness values correlate well with conversion values determined by infrared spectroscopy[17,21,48] and were therefore used in this study to compare the curing lights. The null hypothesis was that there would be no difference in the Knoop hardness values developed in the resin composites when they were irradiated by any of the lights, since all the lights are available for general clinical use.

Table 1 Curing lights, light guides, curing times and power densities measured at 2 and 9 mm from the light guide

Curing light (type)	Light guide	Curing time	Manufacturer	Power densities*
Sapphire (PAC)	9 mm	3 s	Den-Mat, Santa Maria, CA, USA	2 mm 1497 mW/cm^2 9 mm 1189 mW/cm^2
Optilux 501 (QTH)	8 mm standard	40 s	SDS Kerr, Danbury, CT, USA	2 mm 711 mW/cm^2 9 mm 314 mW/cm^2
Optilux 501 (QTH)	13/8 mm turbo +	40 s	SDS Kerr	2 mm 1014 mW/cm^2 9 mm 199 mW/cm^2
Phase II (high-intensity QTH)	8 mm	5 s	Den-Mat	2 mm 1048 mW/cm^2 9 mm 231 mW/cm^2
Versalux (LED)	8 mm turbo	40 s	Centrix, Shelton, CT, USA	2 mm 78 mW/cm^2 9 mm 30 mW/cm^2
FreeLight (LED)	8 mm turbo	40 s	3M ESPE, St Paul, MN	2 mm 292 mW/cm^2 9 mm 43 mW/cm^2

*power densities reported as a mean of 5 recordings using the Cure Rite radiometer

Table 2 Resin composites, shade, and manufacturer

Composite (Shade)	Manufacturer
Filtek Z250 (A1)	3M Dental Products, St Paul, MN, USA
Solitaire 2 (B2)	Heraeus Kulzer, Dormagen, Germany
Prodigy Condensable (A1)	Kerr, Orange, CA, USA
Pyramid Dentin (A2)	Bisco, Schaumburg IL, USA
Pyramid Enamel (neutral)	Bisco

MATERIALS AND METHODS

Six different curing light/tip combinations were used to photopolymerize five different resin composites, and their Knoop hardness numbers (KHN) were compared. The lights and light guides are listed in Table 1 together with the mean power density measurements made with the Cure Rite digital radiometer (serial no. 5330, Dentsply Caulk, Milford, DE, USA). The resin composites are listed in Table 2.

The manufacturer of two of the lights used in this study recommends that the tip of the light guide should be held 2 to 5 mm away from the tooth when irradiating resin using its high intensity QTH light or its PAC light.[15,16] It has been previously reported that the distance from the cusp tip to the gingival floor of a proximal box of a molar tooth can exceed 7 mm.[41,64] Figure 1 shows distances of 6.2 to 6.9 mm from the preparation floor to the tip of the light guide in three representative preparations on molar teeth extending just past the cementoenamel junction. Therefore, 2 mm was used to represent the closest irradiation distance, and 9 mm was chosen to represent a clinical situation with a 7-mm-deep proximal box and the tip of the light guide 2 mm away from the tooth. Taking the manufacturer's claims into consideration, the samples cured with the Sapphire PAC light were irradiated for 3 s and the samples cured with the Phase II high intensity QTH light were irradiated for 5 s.[15,16] The samples were irradiated for 40 s using the Optilux 501 QTH light with both standard and turbo light guides, and the Versalux and FreeLight LED lights. The power densities were measured twice each day during the experiment using a Cure Rite radiometer.

The specimens were made in metal washers with a mean inner diameter of 7.0 mm ± 0.19. This inner diameter was smaller than the diameter of any of the light guides so that they completely covered the composite specimens. The washer was placed on a Mylar strip over a uniformly matte black background and the composite was packed into the hole in the washer. A second Mylar strip was then placed on top of the composite. A glass slide was pressed on top of this Mylar strip to smooth the top surface of the composite, but the slide was removed before irradiating the composite. Curing the composite through the Mylar strip produced a smooth surface and prevented an air-inhibited layer from forming on the surface of the composite. The curing lights were clamped directly over the composite specimen, making sure that the tip of the light guide remained parallel to the surface of the composite. Using a dial gauge, the specimen was lowered to either 2 or 9 mm from the tip of the light guide. As soon as each sample had been cured, the Mylar strips were removed from the top and bottom surfaces. The specimens were stored in a light-proof container in air at room temperature and only removed to measure the KHN. Five samples of each resin composite were irradiated using the same light, height, and composite combination.

The Knoop hardness was measured at the surface of the resin composite within 1 mm of the center of the 7 mm diameter specimens, because previous research has shown that some molds, eg, white vs black Teflon or stainless steel, may absorb, transmit, or reflect light and affect the physical properties of the resin composite.[23,39,64] There is an exponential decrease in light transmission as the thickness of the tooth or resin composite increases.[39,42,62] Consequently, it has been reported that 2 mm of composite reduced the power density to 6% of its original value.[39] Another study found similar results and reported that 2.5 to 3.0 mm of various resin composites reduced the power density to 5% of its original value.[42] The area where the hardness was measured in this study was surrounded by about 3 mm of composite. Therefore, the walls of the metal mold had little effect on the hardness at the center of the specimen.

The hardness at the surface of the composite specimens was measured on the Tukon Hardness Tester (Wilson Mechanical Instrument Division, American Chain and Cable Company, Bridgeport, CT, USA) with a Knoop diamond indenter under a 100-g load[18,21] and 10X magnification. To determine the ability of a curing light to adequately polymerize a composite so it will withstand the forces applied while finishing and adjusting the occlusion, the hardness was measured 15 min after light irradiation. The specimens were then stored in air for 24 h to investigate the effects of time on their continued polymerization. Each sample was measured at each time interval on the top surface, then the bottom three times within 1 mm of the center of the sample. The samples were returned to the light-proof containers immediately after the measurements had been taken. After the measurements had been made at 24 h, the thickness of the specimens was measured using a digital micrometer (No. 293-711, Mitutoyo, Kyoto, Japan) and the mean thickness ± standard deviation was calculated. Specimens that were more than two standard deviations away from the mean thickness were rejected and the specimen was remade.

All the Knoop hardness data obtained were compared using a general linear model (GLM) analysis. The GLM procedure with Sidak's adjustment for multiple comparisons[57] using $p < 0.05$ as the level of significance was used to determine whether all the curing lights produced the same KHN values.

RESULTS

The mean thickness of the resin composite specimens was 1.78 mm ± 0.12. This was within the 2 to 2.5 mm maximum thickness that can be adequately polymerized in one increment according to the manufacturers' instructions.[43,44,58,65] The power densities measured at 2 and 9 mm from the tip of the light guide are reported in Table 1. The QTH light used for 40 s (Optilux 501) always delivered the greatest total energy. There was no difference between the three measurements of hardness made at the same time interval. Therefore, exposing the specimens to light as they were being measured in the Knoop hardness tester had no effect ($p > 0.01$).

Figures 2 to 6 show the percentage hardness of the maximum mean KHN for Z250, Pyramid Dentin, Pyramid Enamel, Solitaire 2, and Prodigy Condensable when the different curing-light/tip combina-

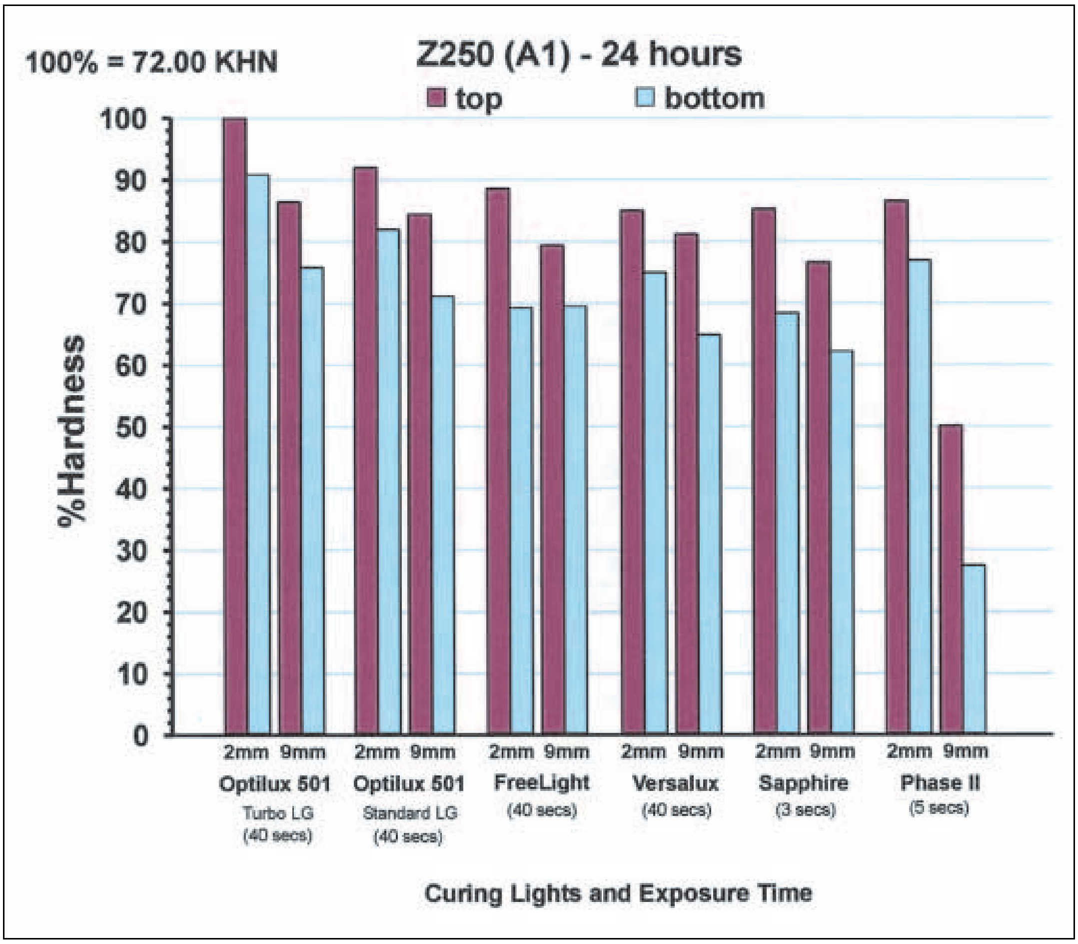

Fig 2 Mean Knoop hardness for Shade A1 of Z250 as a percentage of the maximum KHN.

tions irradiated these composites. The maximum hardness for each composite was always recorded on the top surface 2 mm from the tip of the light guide using the Optilux 501 with the turbo light guide. In Figs 2 to 6, the maximum Knoop hardness number is reported for each composite and the other hardness values are shown as a percentage of this maximum KHN. Figures 2 to 6 also illustrate that the 6 curing light/tip combinations did not cure the five different composites similarly and the two LED lights did not polymerize the neutral shade of Pyramid Enamel. Overall, the Knoop hardness values were greater for Z250 than for the other composites and there was more uniformity in the hardness data for Z250 when irradiated by the 6 different light/tip combinations.

Figure 7 illustrates the overall effect of time on the Least Squares Means Knoop hardness at 15 min and 24 h for the five composites when irradiated with the six curing-light/tip combinations. Since the ranking of the lights between the five composites was different, the lines cross over and illustrate the presence of interactions. Therefore, the hardness of a composite was dependent not only on the different curing light/tip combinations, but was also affected by the side tested, the distance from the light guide, and the storage time. There were significant two and three way interactions between some of these factors ($p < 0.0001$). The pattern of the interaction plot (Fig 7) at 15 min was similar to the pattern at 24 h because the KHN increased similarly for all the composites as the storage time increased ($p > 0.7126$). The hardness also increased similarly at both the top and bottom surfaces ($p > 0.2154$).

Figure 8 illustrates the overall effect of distance between the light guide and composite at 24 h. As the distance increased from 2 mm to 9 mm, the pattern of the interaction plot in Fig 8 changed, illustrating that the decrease in hardness was not similar among the different light/tips and composites ($p < 0.0012$).

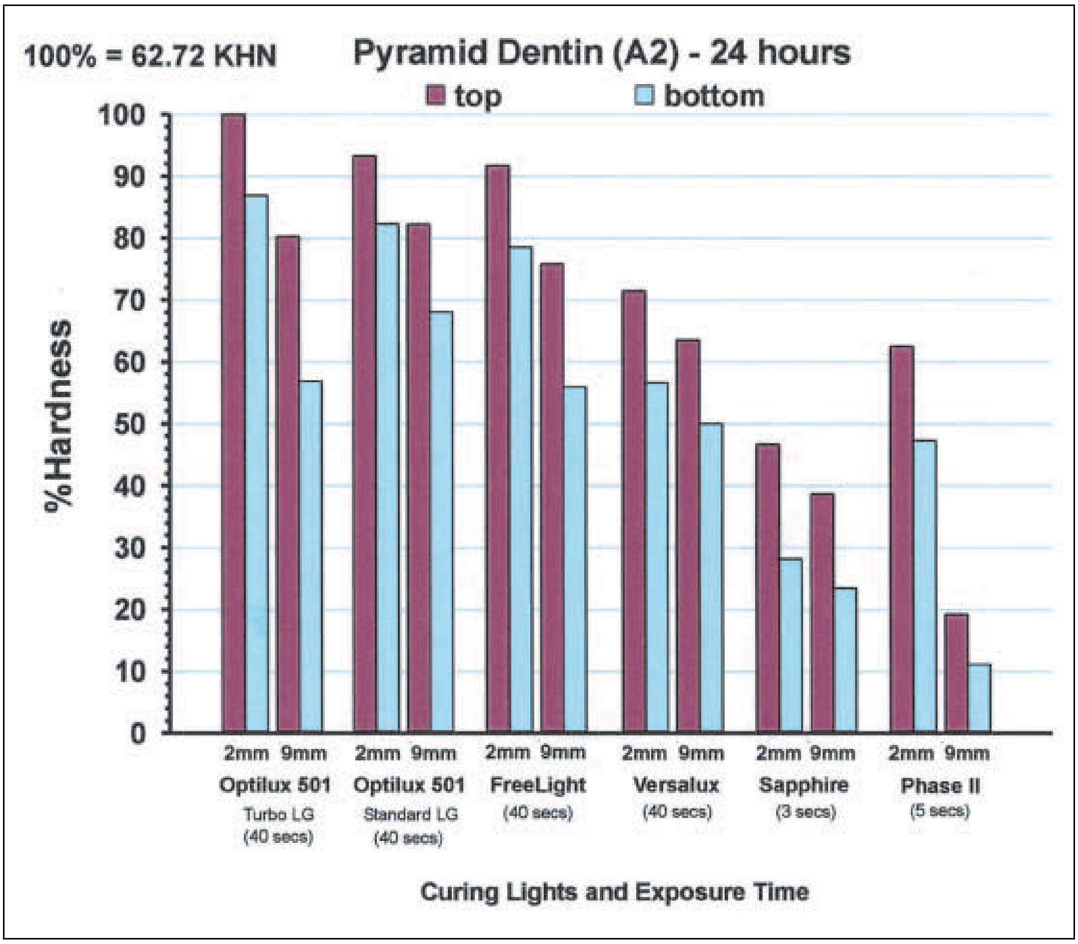

Fig 3 Mean Knoop hardness for Shade A2 of Pyramid Dentin as a percentage of the maximum KHN.

Since neither of the two LED lights could adequately polymerize the neutral shade of Pyramid Enamel in 40 s, there was an obvious difference in the ability of the lights to cure the composites. To overcome the negative effects of the Pyramid Enamel on the analysis, the Pyramid Enamel data was removed and the overall ability of the curing lights to cure the remaining four representative composites, irrespective of distance from the light guide or surface, was compared. Table 3 shows the mean energy density received by the composites and the overall Least Squares Means Knoop hardness at 24 h 2 mm from the light guide and Table 4 presents these values at 9 mm. There was a significant difference between all the LSM Knoop hardness values produced using the six different curing light/light guide combinations at 2 mm ($p < 0.01$). At 9 mm there was no significant difference between the KHN obtained when the Optilux 501 was used with either the standard or the turbo light guide ($p > 0.01$). At 9 mm, there was also no significant difference between the KHN obtained when either of the two LED lights were used ($p > 0.01$).

DISCUSSION

This study used six light/tip combinations to irradiate five representative resin composites at distances of 2 and 9 mm to determine if there was a difference in their overall ability to polymerize the composites. The results of this study clearly showed that when using the manufacturers' recommended curing time, this sample of QTH, PAC, and LED curing lights produced significantly different hardness values ($p < 0.01$) in the five resin composites tested (Figs 2 to 6). The LED lights did not photopolymerize the neutral shade of Pyramid Enamel, and there was an obvious difference in the curing ability of the lights. Therefore, the null hypothesis that there would be no difference in the Knoop hardness values developed in the resin composites when

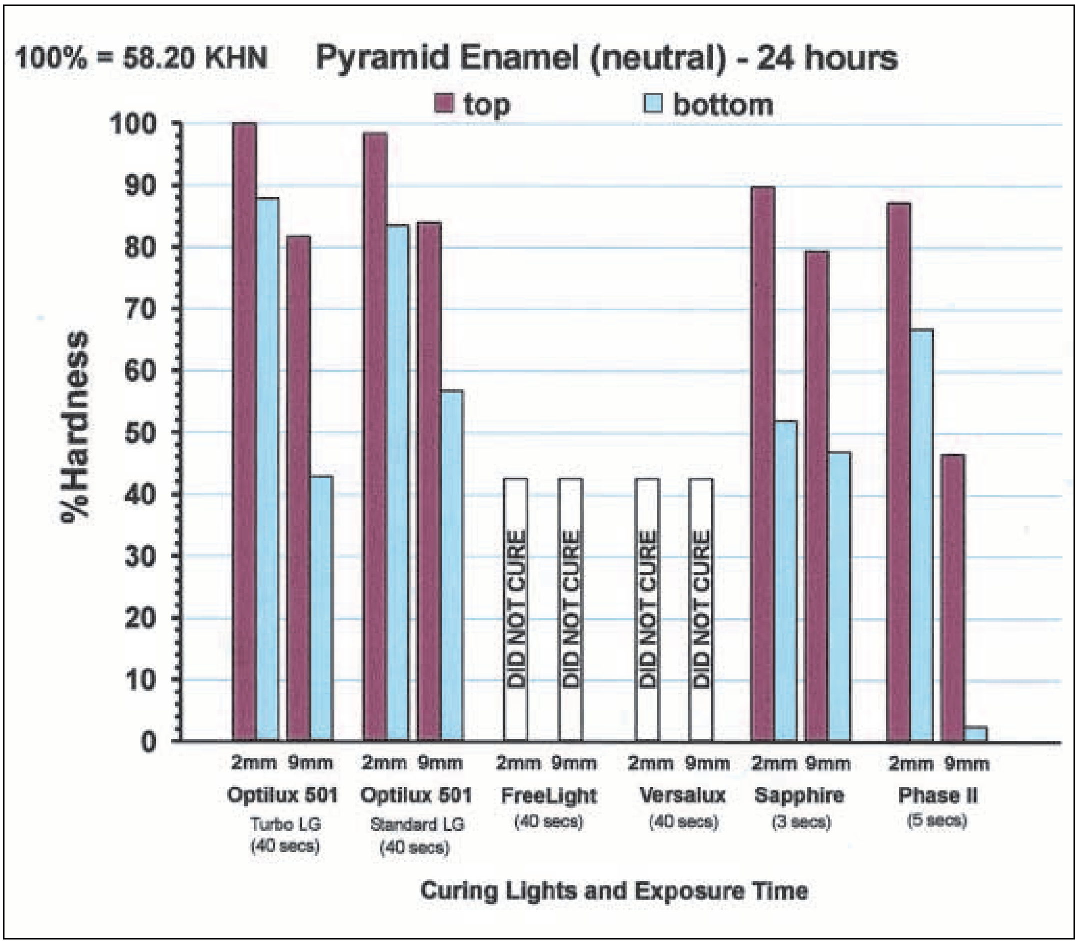

Fig 4 Mean Knoop hardness for Neutral Shade of Pyramid Enamel as a percentage of the maximum KHN.

Table 3 Combined top and bottom Knoop hardness at 24 h of four composites irradiated 2 mm from the light guide

Curing light/Tip combination	Energy density	Overall LSM Knoop hardness
Optilux 501/Turbo:QTH	40.5 J/cm^2	54.02
Optilux 501/Standard:QTH	28.4 J/cm^2	50.25
FreeLight:LED	11.7 J/cm^2	44.30
Versalux:LED	3.1 J/cm^2	38.21
Phase II:QTH	5.2 J/cm^2	34.39
Sapphire:PAC	4.5 J/cm^2	26.24

All lights were significantly different ($p < 0.01$)

they were irradiated by any of the lights tested in this study was rejected. The manufacturer is aware of the incompatibility between the spectral output from some LED lights and the spectral sensitivity of the photoinitiator in the neutral shade of Pyramid Enamel (personal communication, Bisco 2002).

The 9-mm distance between the resin composite and the tip of the light guide may seem large, but this depth can occur in a clinical preparation. If the light guide is 3 mm away from the surface of the tooth, then the bonding agent or composite resin may easily be 9 mm away from the light guide at the

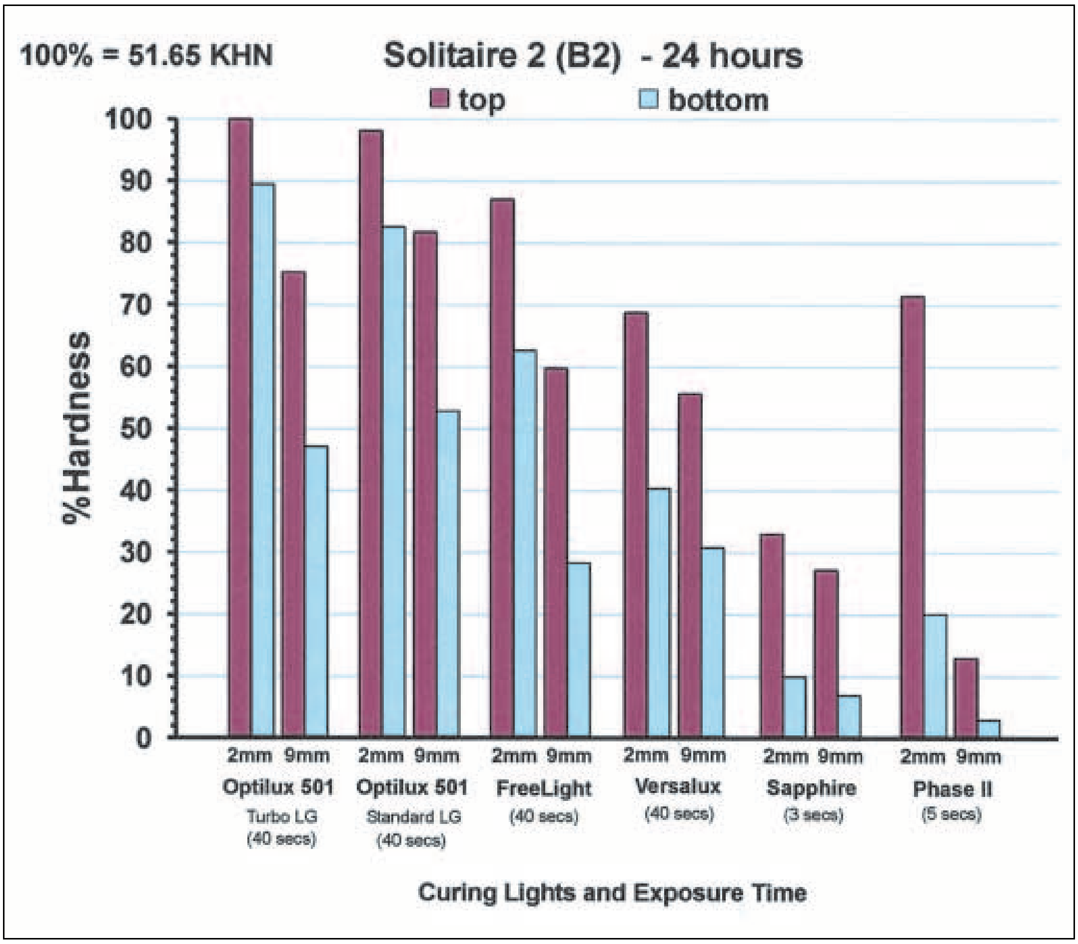

Fig 5 Mean Knoop hardness for Shade B2 of Solitaire 2 as a percentage of the maximum KHN.

Table 4 Combined top and bottom Knoop hardness at 24 h of four composites irradiated 9 mm from the light guide

Curing light/Tip combination	Energy density	Overall LSM Knoop hardness
Optilux 501/Turbo: QTH	7.9 J/cm^2	41.16
Optilux 501/Standard: QTH	12.6 J/cm^2	42.41
FreeLight: LED	1.7 J/cm^2	33.80
Versalux: LED	1.2 J/cm^2	33.17
Sapphire: PAC	3.6 J/cm^2	22.58
Phase II: QTH	1.2 J/cm^2	11.52

Rows connected with a bar are not significantly different (p > 0.01)

floor of a deep preparation. Since there were significant two- and three-way interactions between the factors studied, as illustrated by the crossing over of the lines in the interaction plots (Figs 6 and 7), it was not possible to say that one curing light/tip combination was always better than another light. However, despite these significant interactions, the light that delivered the greatest energy, Optilux 501, always produced the hardest specimens.

The poor results for the PAC light (Figs 2 to 6) are supported by other recent reports[30,40,52,59] and contradict the manufacturer's claims[15,16] that 3 s of irradiation with the Sapphire PAC light or 5 s of irradiation with the Phase II light provides equiva-

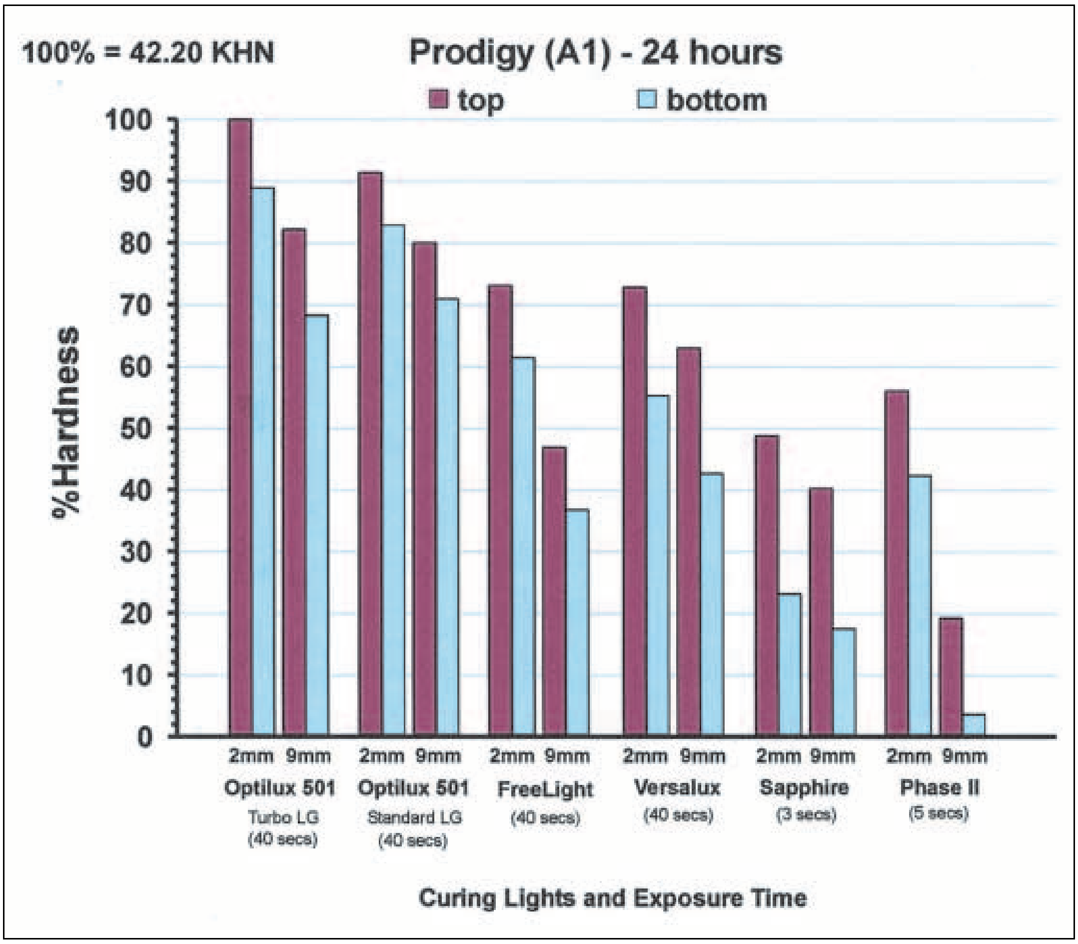

Fig 6 Mean Knoop hardness for Shade A1 of Prodigy Condensable as a percentage of the maximum KHN.

lent polymerization to 30 to 40 s of irradiation using a conventional curing light. The poor performance of the PAC and the high intensity QTH light and the inability of the LED lights to polymerize one resin composite supports Suh's proposal[60] that all resin composites should carry a label stating the energy density and spectral bandwidth required to polymerize the resin composite. It would then be possible to select the appropriate curing light and, if the power density is known, calculate how long to irradiate the composite. Assuming that spectral outputs were the same, if the power density of the Phase II light were 1048 mW/cm^2 at 2 mm, this light would have to irradiate the composite for 27.1 s to provide the same energy density of 28.4 J/cm^2 provided by the Optilux 501 QTH with standard light guide (711 mW/cm^2 for 40 s). If the power density of the Sapphire light were 1497 mW/cm^2 at 2 mm, this light would have to irradiate the composite for 18.8 s to provide the same total energy density of 28.4 J/cm^2. The Optilux 501 with the turbo light guide delivered 1014 mW/cm^2 for 40 s (40.6 J/cm^2). At 2 mm, the energy density from the Sapphire light was 4.5 J/cm^2 (1497 mW/cm^2 x 3 s) and 5.2 J/cm^2 (1048 mW/cm^2 x 5 s) from the Phase II light. This compared to the total energy density of 28.4 J/cm^2 from the Optilux 501 with the standard light guide and 40.5 J/cm^2 using turbo light guide and 11.7 J/cm^2 using FreeLight. Although at certain distances from the light guide or surfaces of a particular composite, one light guide/tip combination might perform better than their overall rank indicates, Tables 3 and 4 provide an overall rank of the ability of the lights to polymerize four representative composites at 2 and at 9 mm. The Optilux 501 light delivered the most energy to the composites, and it is therefore not surprising that the Optilux 501 always produced the hardest composite specimens. These results support previous reports that when a resin composite receives inadequate energy density, the hardness is adversely affected.[9,14,37,55]

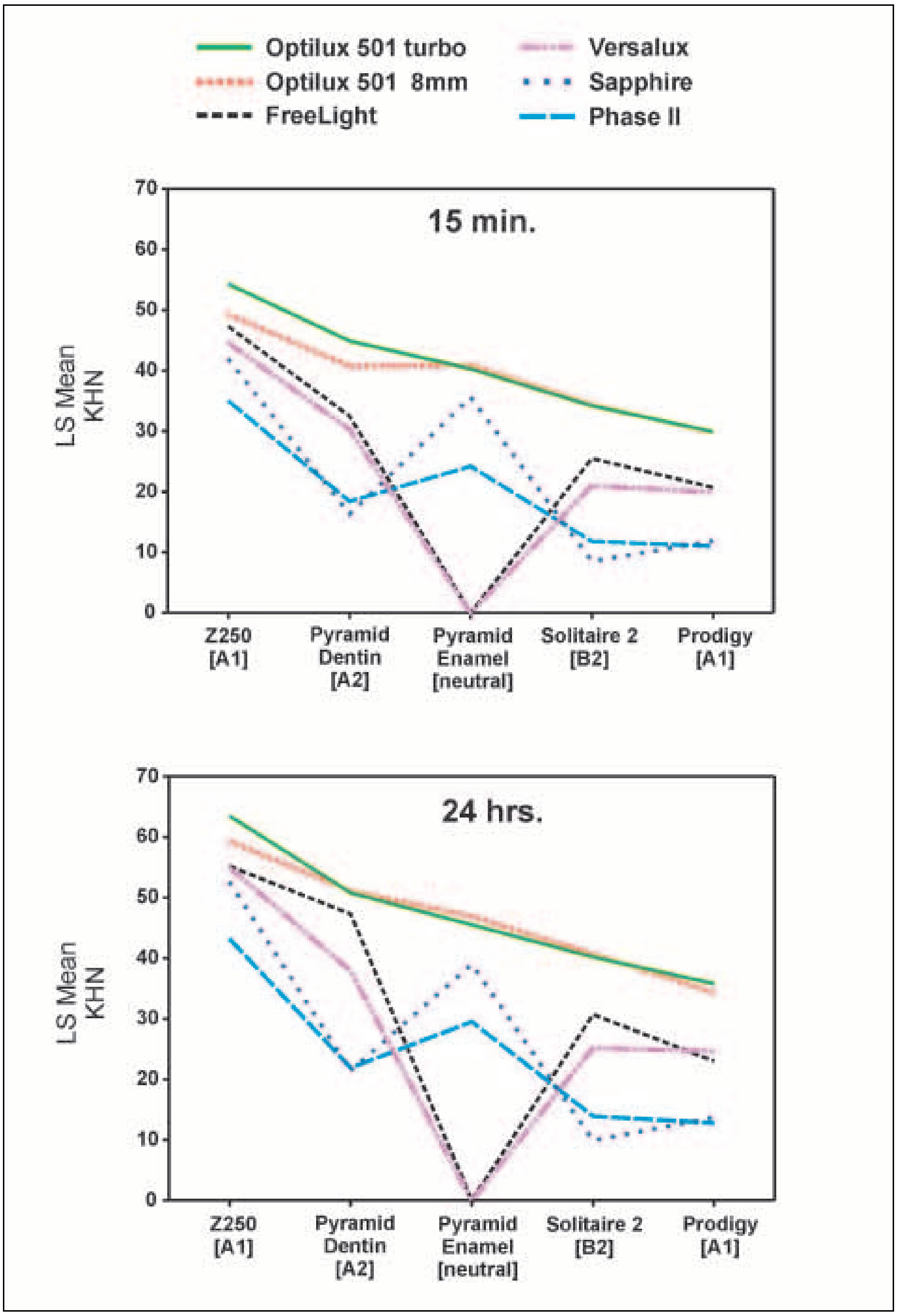

Fig 7 Overall Least Squares Means Knoop hardness at 15 min and 24 h for 5 composites irradiated using 6 curing light/tip combinations.

It is also interesting that at 2 mm, both the Sapphire and the Phase II had a greater energy density at 2 mm than did the Versalux, yet they were not able to cure the composites as hard as the Versalux. At 9 mm, both the Versalux and the Phase II delivered equivalent energy densities to the composites (Table 4), yet the overall LSM KHN was almost three times greater when irradiated by the Versalux. It may be that the light energy delivered over a greater period of time (1.2J/cm^2 in 40 s with Versalux) yields a harder composite than if the same energy is delivered over a much shorter period of time (1.2J/cm^2 in 5 s with Phase II). Further studies are needed to address the relationship between exposure time and power density in delivering energy to the composite. It could also be that even though the energy delivered at 9 mm by both the Versalux and Phase II was the same, the spectrum of light from

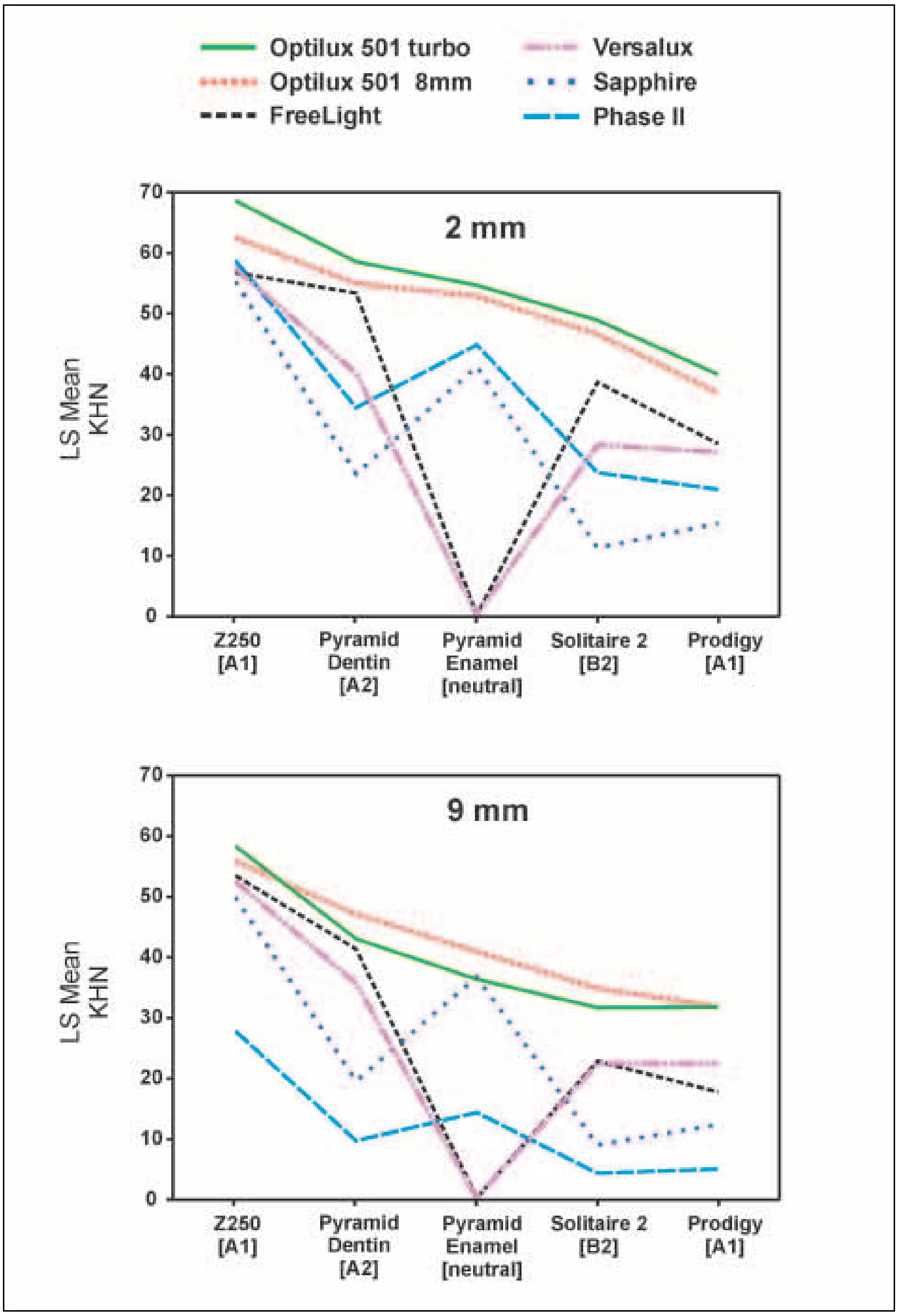

Fig 8 Overall Least Squares Means Knoop hardness at 24 h for 5 composites irradiated 2 and 9 mm away from the tip of the light guide.

the Versalux may be more effective in activating the photoinitiator in the resin. However, further studies are needed to examine the spectral outputs of the new curing lights which are now available.

The KHN increased similarly (Fig 7) for all the composites as the storage time increased ($p > 0.7126$). This increase in hardness over time due to post-irradiation polymerization has been previously reported and was expected.[14,36] These results suggests that final polishing of a resin composite restoration should be delayed for 24 h, although a clinical trial is required to determine if the increase in hardness and ability to be polished at 24 h is clinically relevant.

It has been reported that there should be no more than a 20% difference between the maximum hardness at the top of the composite and the hardness at the bottom of the specimen for the composite to be adequately cured.[36,53,63] At 2 mm, only the Optilux 501 with either the standard or turbo light guides could cure any of the composites to the extent that the bottom of the 1.78 ± 0.12-mm-thick specimens of composite had at least 80% of the maximum hardness at the top surface. At 9 mm, none of the lights could produce a composite which had a hardness at the bottom surface which was at least 80% of the maximum hardness. These results support previous recommendations that resin composites should not be irradiated in greater than 2 mm increments.[9,37,46,49,50] These recommendations were made with the light guide in close proximity to the composite surface. However, at a clinically relevant distance of 9 mm, neither the top nor the bottom of the composites tested achieved this 80% hardness, indicating that at the bottom of a deep preparation, some resin composites may not achieve an acceptable degree of polymerization. This may cause increased cytotoxicity and increased postoperative sensitivity especially if a weak curing light is used.[7,8]

Despite high power densities of 1048 mW/cm^2 at 2 mm from the Phase II light, 1014 mW/cm^2 at 2 mm from the Optilux 501 light with the turbo light guide, compared to a lower power density of 711 mW/cm^2 from the Optilux 501 with a standard light guide, Table 1 shows that these power densities fell to similar values at 9 mm. This suggests that the light dispersed more rapidly from the tip of the Phase II light and the Optilux 501 with a turbo light guide than from the standard light guide. Since the effect of distance on hardness depended on which curing light/tip was used (eg, Phase II), it is not possible to predict the clinical performance of a curing light at 9 mm based upon power density measurements or hardness data recorded with the tip of the light guide in close proximity to the meter or resin composite. Therefore, future comparisons of dental curing lights should be made at clinically representative distances.

Based on the results from the Cure Rite radiometer, it appears that the power densities from the PAC and QTH light sources were well above those used in many dental offices[37] and they were all more than the minimum 280 to 300 mW/cm^2 power density values previously reported as necessary to polymerize resin composite. Although the Sapphire PAC and Phase II high intensity QTH lights delivered the highest power densities at 2 mm, when they were used for the manufacturers' recommended curing time, neither of these two lights performed as well as the Optilux 501. This observation is likely to be explained by the fact that although the Sapphire and Phase II lights produced a higher power density than the Optilux 501, the exposure time was too short (3 and 5 s, respectively, compared to 40 s with Optilux 501) and much less total energy was delivered to the composite while curing. Despite a low power density recorded by the Cure Rite, the Versalux LED light performed well. This indicated that the spectral output from this light matched the photoinitiators contained in the composites used in this study. Consequently, most of the energy produced by the Versalux light was useful energy, and although low, it was sufficient to polymerize the composites. This observation illustrates the limited usefulness of the Cure Rite (and similar) radiometers for measuring the power output from LCUs with spectral outputs which are different from QTH lights. Until dental manufacturers can provide radiometers which will accurately measure the power density from PAC, laser, and LED lights, power densities should be measured with a laboratory grade spectrometer with an integrating sphere.

CONCLUSIONS

Within the limitation of this study, which used six different curing light/tip combinations to polymerize five representative resin composites, it is concluded that:

1. The 6 curing light/tip combinations had different effects on the hardness of the 5 composites ($p < 0.01$).
2. Neither of the two LED lights used was able to adequately polymerize the neutral shade of Pyramid Enamel.
3. Although there were significant interactions between the factors examined, irradiating five representative resin composites with the conventional QTH light (Optilux 501) for 40 s always produced the hardest resin composite specimens.
4. When the distance from the light guides increased, the effect on the hardness of the resin composite was not the same for all light/tip combinations ($p < 0.0012$). It is therefore not possible to predict the performance of a curing light at 9 mm based upon power density measurements or hardness data recorded at 2 mm.
5. When a resin composite receives inadequate total energy, the hardness is adversely affected,

regardless of power density emitted by the curing light.
6. All resin composites should carry a label stating the energy density and spectral bandwidth required for adequate polymerization.

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