AN INVESTIGATION ON LIGHT INTENSITY VARIATION WITH COMPOSITE RESIN DEPTH IN DENTAL CURING DEVICES

by

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ABSTRACT

AN INVESTIGATION ON LIGHT INTENSITY VARIATION WITH COMPOSITE RESIN DEPTH IN DENTAL CURING DEVICES

In this thesis whether a new generation LED light source based Light Curing Unit can cure a new generation Dental Restoration Composite in a deep cavity situation, by a single application, without adverse effects and save time both for the Doctor and the patient, is investigated. An experimental setup, including a made-to-specification LCU using the highest intensity single LED available is prepared to find the light intensity change through a new generation Dental Composite, from 0 to 8 mm, in 1 mm increments

It is observed that the light intensity falls by exponentially in the composite, leaving only 15% of the light entering at the top surface in 4^{th} mm and 5% in the 5^{th} mm. With a given exposure duration of 20s, this proves not enough to polymerize the composite at lower levels As the composite polymerizes its opacity decreases to result in an increase in light intensity on the other side of the material by 4%. This phenomenon stabilizes in 40s at 1 mm, 72s in 2 mm, 84s in 3 mm. This may be an indication of full polymerization. When longer cure duration of 90s and 180s is applied composite polymerizes up to a depth of 5.50 mm, while increase in light intensity trend behind 6 mm composite thickness continues (482% increase in 180 s) Results indicate that, if a LCU with enough power to compensate the loss in the material is used, it may be possible to cure deep restorations in a single application at shorter total duration.

Keywords: Dental Curing Light, LED, Dental Restoration Composite, Light Intensity Attenuation / Absorption / Penetration, Polymerization.

ÖZET

DENTAL IŞIN TABANCALARINDA IŞIK YOĞUNLUĞUNUN KOMPOZİT DERİNLİĞİ İLE DEĞİŞİMİ KONUSUNDA BİR ARAŞTIRMA

Bu çalışmada yeni jenerasyon LED ışık kaynaklı bir Işınlı Dolgu Cihazı, yeni jenerasyon bir dental kompoziti derin bir dolgu uygulamasında, istenilmeyen yan etkiler oluşmadan tek bir uygulama ile dondurabilir mi, incelendi. Işık şiddetinin yeni jenerasyon bir kompozit diş dolgusu içinde 0'dan 8 mm'ye kadar derinlikte 1 mm'lik adımlarla, değişimini gözlemlemek üzere, bir deney düzeneği kuruldu. Bilinen en yüksek ışık şiddetine sahip tek bir ticari LED içeren özel bir ışınlı diş dolgu cihazı yaptırıldı.

Kompozit içinde ışık eksponansiyel bir eğri ile azalıyor. 4.mm'de ışık şiddetinin sadece %15'i kalır iken 5.mm'de bu değer %5'e düşüyor. 20 saniyelik bir uygulama süresince bu değerler kompositin polymerize olmasına yetmiyor. Kompozit polymerize olur iken 1 mm dolgudan geçen ışık şiddeti %4 kadar artıyor. Bu olgu 1 mm'de 40s, 2 mm'de 72s, 3 mm'de 84 s içinde stabilize oluyor, ki bu da tam polimerizasyonun gerçekleştiğini bir göstergesi olabilir. 90 ve 180 s lik daha uzun uygulama süreleri içinde kompozit 5.5 mm derinliğe kadar sertleşir iken, kompozit kalınlığı arkasında okunan ışık şiddeti zamanla artmaya devam ediyor (artış oranı 6 mm'de 180 s içinde %482). Sonuçlar yeterli güçte bir ışık kaynağı ile ışığın kompozit içindeki mesafe ile soğurulması kompanze edilerek daha derin dolgulara gerekli ışık şiddeti sağlanabileceği ve tek bir uygulamada derin dolguların gerçekleşebileceği öngörüldü.

Anahtar Sözcükler: Işınlı Diş Dolgu Cihazı, Kompozit Diş Dolgusu, LED, Işık şiddeti / Soğurulması / Geçirgenliği, Donma,

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LIST OF ABBREVIATIONS

GMA	Bisphenol A diglycidyl ether dimethacrylate
TEGDMA	Triethylene glycol dimethacrylate
UDMA	Urathane dimethacrylate
BIS-EMA	Bisphenol A polyethylene glycol diether dimethacrylate
LCU	Light Curing Unit
RC	Restorative Compozite
DC	Degree of Conversion
DOC	Depth of cure
A	Amper
V	Volt
mV	milivolt
cm	Centimeter
mm	milimeter
W	Watt
nm	Nanometer
s	seconds

1. INTRODUCTION

Dental Composites and Light Curing Units are very common and popular applications in modern dental practice. There is continuous progress in the area of both composite material and curing devices, mostly including high technology applications of chemistry, nano-technology, bio-sciences, material science and electronics

In the second section a short background about the state of the art on both materials investigated and devices used are given briefly.

Investigation into the Dental Restorative Composite (RC) polymerization in relation to light intensity and duration is countless Probably due to the fact that the subject falls more closely to the field of material science, more if not all, of these investigations are directed towards study of material properties after being in contact with the Light Curing Unit (LCU), for a recommended cure time. Degree of polymerization or Degree of Cure (DC), is determined by the established methods of hardness tests after certain exposure times with varying light intensities [1] [2]. Varieties of factors such as distance of the light from the RC [3] [4], thickness of the RC [4], curing time [5], different LCUs [6], different brand name RCs [7], through ceramic [8], have all been experimented and recorded to a great degree. Almost all of these studies are carried on at the recommended thickness of 1 to 2mm as stated by ISO 4049:2000. For deeper applications most studies suggest polymerization is incomplete [9].

Current work has stemmed from a basic question:

Can a new generation LED LCU cure a new generation RC in a deep cavity situation, by a single application, without adverse effects detailed in Section 2 to the RC itself.

Current rules suggest 1.5 mm of RC should be sufficiently cured by a LCU based on the ISO 4049:2000 [10]. All RC manufacturers claim to comply with this standard, mostly without reference to the minimum power intensity required of the LCU [11].

The implication of the 1.5 mm rule to the Dentist is, that the practicioner has to apply the cure in 1 mm increments, one at a time, layer-by-layer, to be on the safe side (Figure 1.1). While both the patient and the Doctor have to take a longer time for the cure. It is not sure, even with a powerful LCU, what happens to the composite at the bottom of an 8 mm dental filling, if cured in one single application.

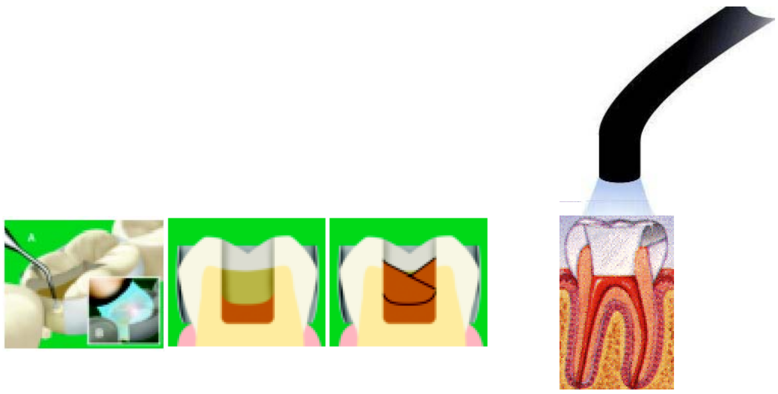


Figure 1.1 Application of Dental Composite Restoration

The answer is assumed to be in the knowledge of how much of the light intensity delivered at the surface is lost, absorbed, as it travels deeper into the RC. If this could be formulated, it would be possible to polymerize RC at the very bottom of the filling in one of the two methods;

- either by increasing the intensity at the LCU to achieve optimal intensity required at a certain depth of RC
- or increasing the time taken for the required exposure to be achieved at a certain depth - that is, if reciprocity rule for exposure/dosage is valid [12]

With this information at hand, a commercial LCU manufacturer can integrate a lookup table in their LCU controller, which will automatically calculate the time required for total polymerization, for a certain RC brand and a certain depth of filling. The device then could increase the light intensity by ramping up the light intensity as the light travels deeper in the RS polymerizing from the upper levels down. Applying a high intensity light at the surface during polymerization, is known to cause internal stress and fractures and cavities due to shrinkage [13]. However once polymerization is complete, increasing the light intensity will not affect the stabilized composite [14].

In other words, once the first milimetre is fully polymerized the intensity can be increased for the second millimeter to receive the same amount of light, without harm to the already polymerized first milimetre. This method can be carried on deeper.

It is necessary to know, what percentage of light is absorbed as it goes through the composite, and if polymerization has an affect on light transparency of the RC. It is the aim of this study to find the answer, with the experimental setup in Section 4.

2. BACKGROUND

Below a short background about the state of the art on both materials investigated and devices used are given briefly.

2.1 Composite Fillings

Composite fillings are dental filling material devised to replace conventional amalgam material and are preferred by the Dental Doctors for their close resemblance of the natural dentin [14]. Commonly referred to as "restorative composite material" (RC), they are commercially available in tubes of a single compound paste that is applied in the cavity, which will polymerize with a special spectrum and intensity of light. Once polymerized the material becomes hard and durable, may have a variety of colours to reflect the actual colour tone of the human dentin, that varies in each individual.

Composite is formed commonly of three main groups of material:

- Resin
- Filler
- Microfill

Resin is the main body that holds together the small particles called "microfill" and the larger ones called "Filler" or "Hybrids". It is the agent that mainly responds to light of special wavelength and is polymerized. The material commonly used in resins are BIS-GMA (Bisphenol a diglycidyl ether dimethacrylate), BIS-EMA (Bisphenol a polyethylene glycol diether dimethacrylate), UDMA (Urathane dimethacrylate) and TEGDMA (Triethylene glycol dimethacrylate).

When initiated, Bis-GMA cross-links to form a hardened resin polymer. Bis-GMA is very thick and is diluted with TEGMA to make it easier for the dentist to work with.

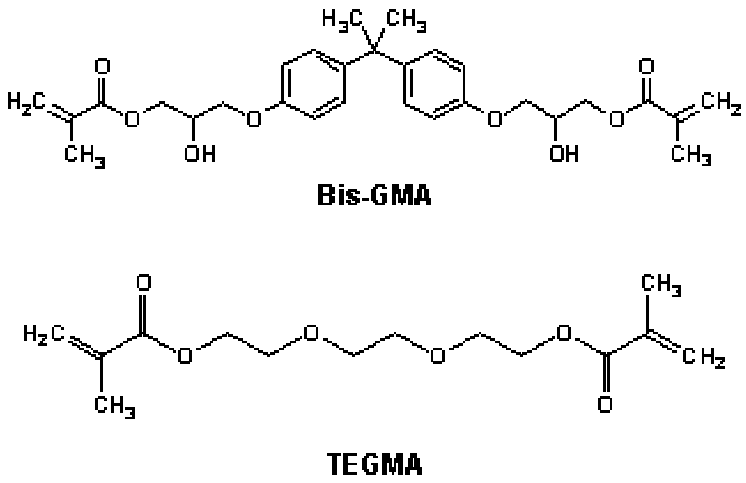


Figure 2.1 Chemical formation Bis-GMA and TEGMA

The final component is an initiator, camphoroquinone (CQ), which generates a radical species when exposed to light with a wavelength of 470 nm. CQ allows dentists to start the polymerization of Bis-GMA exactly when they want to.

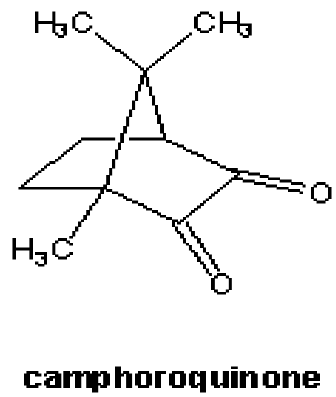


Figure 2.2 Chemical formation of initiator

There are a vast variety of substances used by different manufacturers of composite resins, however they carry the same basic principle of responding to Curing Light Units and polymerize to harden the filling.

Filler is the substance that is added to give the strength and optical properties to the filling. However, it lacks in polish retention. Also called as hybrids or micro hybrids, they contain a broad range of particle sizes, typically below 1 micron but above 0.4 microns In application hybrids are preferred in the body of posterior fillings or inner layer of the anterior, to give strength and colour to the restoration.

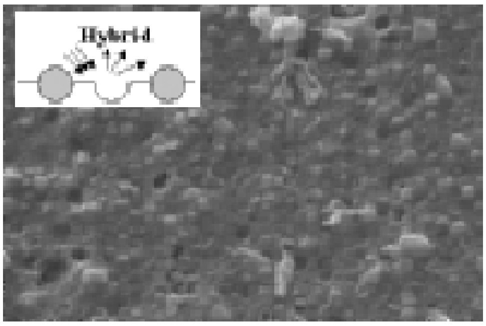


Figure 2.3 Hybrid under microscope *(photo courtesy of 3M)*

Microfills are particles of smaller size, of 40nm, traditionally made from fumed silica, responsible for polish retention. They are preferred in the anterior regions and the final finishing of the posterior to represent the optical properties of the enamel. They do not give sufficient strength required when used alone.

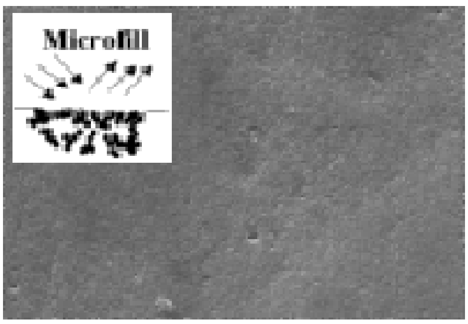
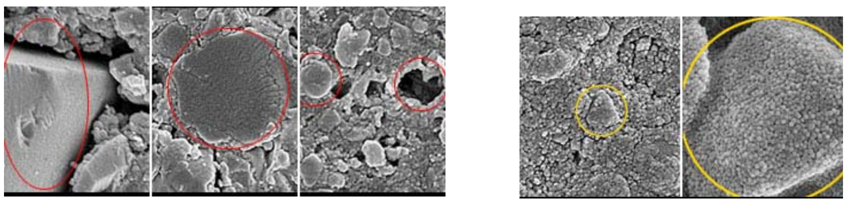


Figure 2.4 Microfill under microscope *(photo courtesy of 3M)*

Application of the dental composite either on the anterior or posterior traditionally requires different materials possessing strength or polish retention, sometimes both simultaneously. Manufacturers have recently introduced “universal” composites having both properties that can be applied on either area, to make the job of a Dental Doctor a little easier.

We chose a new technology material developed with the use of nano-technology, manufactured by 3M. Instead of the filler and microfill applications, particles of 20nm sizes are present in one universal composite. With the application of LCU some nano-particles are gathered in nano-clusters to form bigger particles of sizes to give the strength of the filler material. This is aimed to give the material polish retention and strength in one application suitable for both anterior and posterior dentin.

The new composite is made using nano-clusters alone. During polymerization part of the nano-sized particles agglomerate together to form nano-cluster. These clusters form the filling, but can separate during abrasion, thus giving the composite both polish retention and strength.



Conventional application   Nano cluster application

Figure 2.5 Conventional vs. Nanocluster RC under microscope *(photo courtesy of 3M)*

Colour is a main property that dentists seek while restoration of a dentin. Every individual has a different colour profile even that varies from one area of the mouth to the other, within the same individual. Factors such as mouth cavity darkness and dental base darkness that reflects to the final appearance of the tooth and has to be taken in consideration while deciding which composite, which shade to be used. Sometimes more than one composite is used, one at the base and another on the surface to closely reflect the appearance of the natural tooth. Shades of gray, yellow and violet are commonly used for matching human dentin.

Mostly before the application of the composite tooth has to be grinded to have a rough surface that the material can cling on, acid is used to further even out the roughness, a bonding agent is used that clings on the dentin surface and bonds with the final composite to be applied. Complex and detailed procedures and a vast variety of material make the job both a science and art when it comes to restoration of teeth.

Our choice of dental composite for this thesis was made under the light of this information, as detailed in the section that describes our method.

2.2 Light Curing Units

Dental Light Curing Units (LCU) are devices applied in dental practice for polymerizing composite material, used in dental fillings

Most composites will polymerize with 468nm, the peak absorption band for the camphoroquinone [15]. The composite material used in this study, is polymerized with a light in the spectrum of between 450-470 nm.

Currently there are three common light sources used to supply the light to polymerize the dentin:

- Quartz Tungsten Hallogen (QTH)
- Plasma Arc (PAC)
- Light Emitting Diode (LED)

QTH light source curing lights use a 50W halogen lamp with a light filter to narrow the light spectrum to 450-470nmband required for composite polymerization.

They generally have a cooling fan as the light heats up considerably, also transferring some of that heat to the dental area [16]. They need to carry cord cable as their consumption is to high to be supported by batteries in a handheld unit. Manufacturers generally claim light power levels of between 500 to 1500mW cm^{-2} and curing times of 40 seconds [17].

PAC light source units have a considerably higher light outputs reaching 1900mW cm^{-2} and recommended cure times drop to as low as 3 seconds [18].

LED light units have been possible only with the recent introduction of high light luminosity LEDs The first generation LED curing units incorporated as many as 25 high luminosity LEDs, however the new generation units generally use a single high intensity led unit. LED units with their very narrow spectrum that falls very closely on the 460nm band, claim to achieve shorter cure times; commonly half of the recommended duration - 20 seconds Studies have proven their superior heat performances of lower heat being transferred to the dental area [16]. LED LCUs have also enabled cordless, battery-powered operation with their low energy consumption.

In this study to achieve the highest possible light intensity, a prototype unit has been manufactured by a designer of curing lights - Digitech. A Lumiled dental 5W LED has been used in the prototype, claimed by the manufacturer to be one of the highest luminosity LEDs available. The unit is drived at the manufacturers recommended current of 700mA to achieve 600mW cm^{-2}, with a linear driver circuitry having a 10 second count-down timer intervals from 10 seconds to 90 seconds

2.3 Clinical Application and Problems

Dental Doctor has a number of difficulties for the choice of application to achieve a natural looking composite filling as detailed above in our brief of the material selection properties There are other restrictions that apply in practice.

It is desirable to shorten the cure time and minimize the steps taken to complete the filling. Manufacturers of composite material are trying to come up with “universal” composites that can be used in more than one if not all applications and LCU manufacturers are trying to design more powerful units to achieve shorter application times However high light output units such as QTH and PAC, in return can cause problems such as [13];

- internal stress and fractures
- cavity formation
- shrinkage
- and failure of cure
- heating of the surrounding tissue

The Dental Doctor may wish to apply a single composite on a deep cavity, with the help of high intensity deep penetrating LCU, however is not sure either the bottom-most layer is fully polymerized or not. Additionally, it is not desirable to fracture and shrink the top-most layer with high power (that is required to penetrate deeper).

Dental composite manufacturers are suggesting curing procedures, that incorporates special diagonal laying of composite material, 1 mm in each step, to ensure polymerization. These methods are safe, but incumbersome and time consuming to apply.

LCU manufacturers, through years, have come up with devices that have a ramp up light intensity or pulse mode to penetrate deeper and at the same time not to cause stress fractures

It would be possible to depict the right ramp and light intensity levels required at each second, if the light absorption through the composite was investigated and correlated into the LCU. This way it would be possible to cure deep cavities in single application, with precision.

Though not all studies produced agreeing results, it may be said that for manufacturers' recommended thickness of 1,5 mm, also cited as a standard at ISO 4049:2000, satisfactory polymerization is mostly achieved supported by the hardness tests We have taken the view that if sufficient or acceptable intensity of light falls upon a RC of acceptable maximum thickness of 1,5 mm, sufficient polymerization occurs This view is based on numerous prior experiments and studies [18].

In this study we are investigating the answer to a few questions:

- What is the behavior of the composite material during and after polymerization, with regards to optical characteristics Does it become more transparent or opaque, if so to what percentage
- As the light travels deeper in the composite how is it absorbed, which law or formula does it follow. Is it a linear formula or exponential.
- Would it be possible to compensate the loss of light during penetration into the composite by increasing intensity
- Would it be possible to harden higher than the recommended 1.5 mm RC

3. MATERIALS

3.1 Dental Restoration Composite

A new commercially available visible light-cured RCs was studied (Filtek Supreme XT – 3M) A2B shade.

For statistical data analysis, each thickness of RC the experiment is repeated eight times

Figure 3.1 Composite Material

3.2 Dental Phantoms and mold

Special dental phantoms have been fabricated out of brass Rectangular prisms of 24 mm wide by 32 mm long and varying heights of 1 mm to 8 mm, are custom prepared. To the centre of the prisms a cylindrical hole of 4 mm were drilled, to represent dental cavity. This way varying cavity depths of 1 mm to 8 mm in 1 mm increments were obtained.

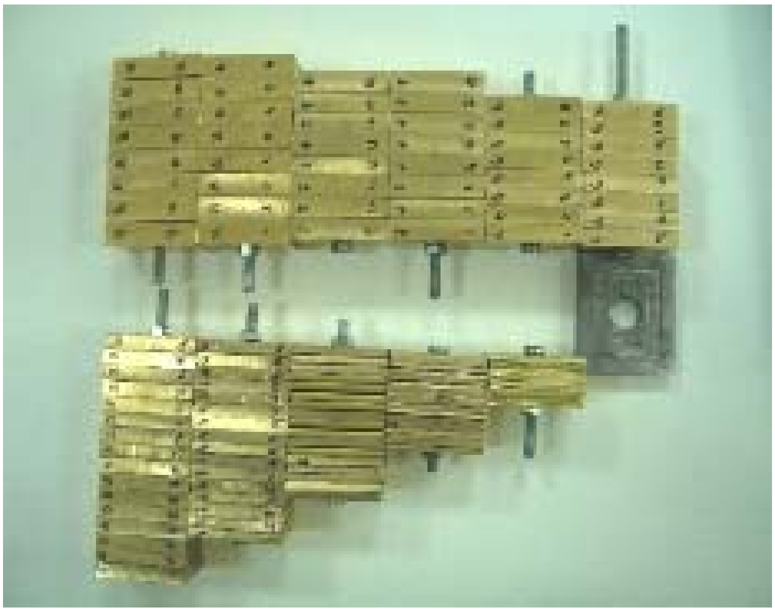


Figure 3.2 Dental Phantoms 1mm to 8mm

To center and align these phantoms to the source of light, another mold, a rectangular prism of 34 mm wide by 42 mm long and 15 mm high is custom manufactured out of steel. A 24.2 mm wide by 32.2 mm long indentation of 2 mm depth is carved inside this mold to place the phantoms

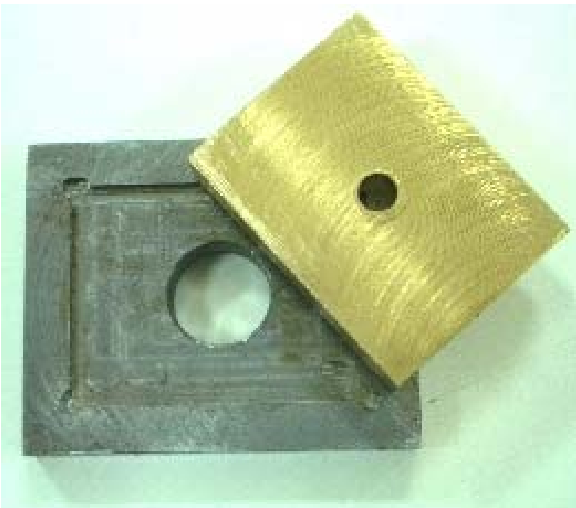


Figure 3.3 Dental Phantom and Mold

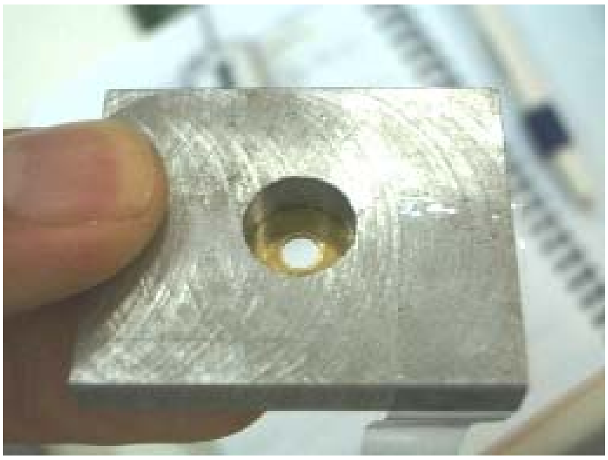


Figure 3.4 Mold for Centering Phantom and Light Guide

This mold also had a cylindrical hole, centre to the surface of 34 mm by 42 mm, 10.5 mm in diameter that would allow the optical fiber light guide (10.0 mm diameter), to fit in.

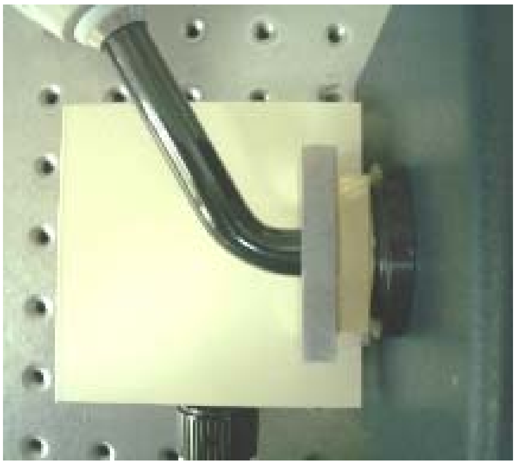


Figure 3.5 Alignment of Mold, Phantom, Light, Light Guide and Integrating Sphere

All metal works prepared to a precision of 0.05 mm.

3.3 LED Light Source

The experiment demanded high depth of RC to be achieved with a LED light source. For this purpose worlds highest luminosity single LED source is searched. A 5W LED light source (Luxeon LXHL-LRD5), having a special light spectrum for dental LCU applications is found relevant to our purpose.

Table 3.1 LED light Source, Catalogue values, wavelength and Angle
(Table courtesy of Luxeon)

Optical Characteristics at 350 or 700mA, Junction Temperature, T_J = 25°C

Part Number	Peak Wavelength[3] λP Min.	Typ.	Max.	Spectral Half-width[4] (nm) $\Delta\lambda_{1/2}$	Temp coefficient of dominant wavelength (nm/°C) $\Delta\lambda_D/\Delta T_J$	Total Included Angle[5] (degrees) $\theta_{0.90V}$	Viewing Angle[6] (Degrees) 2θ 1/2
LXHL-BRD1[1]	450	460	470	20	0.04	110	110
LXHL-MRD1[1]	450	460	470	20	0.04	110	110
LXHL-PRD5[2]	450	460	470	20	0.04	150	150
LXHL-LRD5[2]	450	460	470	20	0.04	150	150

LED was driven with a constant current driver at 660 mA. ((Catalogue value has been tested with a radiometer reading at 460 nm and actual radiometric power or the LCU unit has been recorded at 360 mW at the tip of the optical fibre light guide.))

Table 3.2 LED Light Source Radiometric Power, Catalogue Values
(Table courtesy of Luxeon)

Radiometric Power Characteristics at 700mA, Junction Temperature, T_J = 25°C, Continued

Luxeon V	Configuration	Radiation Pattern	Minimum Radiometric Power (mW) Φ_V [1,2]	Typical Radiometric Power (mW) Φ_V [2]
LXHL-PRD5	Emitter	Lambertian	500	600
LXHL-LRD5	Star	Lambertian	500	600

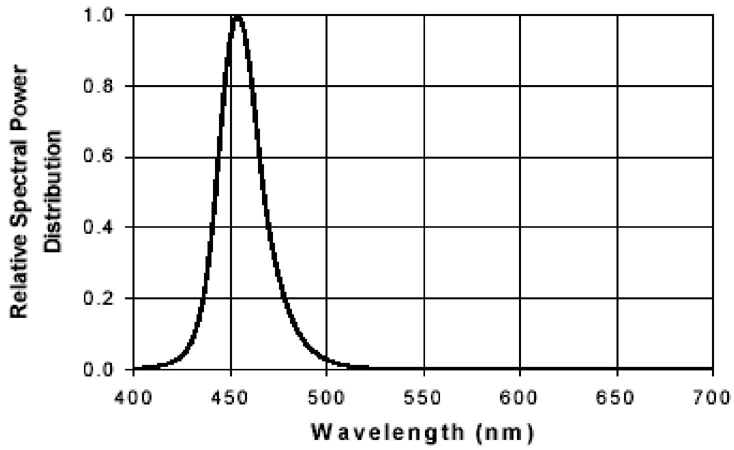


Figure 3.3 LED Light Source Wavelenght Characteristics, Catalogue Values *(Graph courtesy of Luxeon)*

3.4 Ligth Curing Unit

The LCU, was made to order (Digitech Ltd, Kavaklidere, Ankara, Turkey) using the Luxeon LXHL-LRD5 LED light source. The LCU would drive the LED light source at 660 mA constant current which was tested and observed throughout the experiments, with a power supply (Figure 3.8)

LCU had a step down timer programmable function that would enable us to set between 10 seconds to 90 seconds in 10 seconds increments

Figure 3.7 LCU (Digitech Ltd)

Figure 3.8 Power Supply (GW GPC 3030D)

Figure 3.9 Light Sensor (SDAU)

3.5 List of Other Equipment Used

- Data Logger
- PC
- Data recording software (Instrunet)
- Magnetic Base, for stabilizing LCU
- Adjustable base, for support and stabilizing phantom and mold
- Integrating sphere

4. METHOD

Firstly a Cover Slip (ISOLAB Deckglaser, Germany) of 0.15 mm thickness and 24 mm by 36 mm is placed in between the mold and tooth Phantom. Figure 4.1

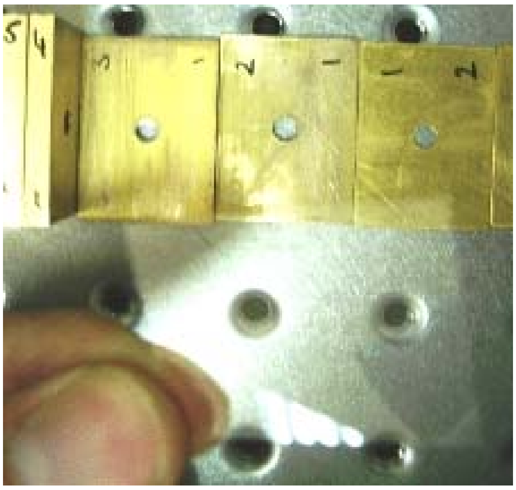


Figure 4.1 Cover Slip

Once the RC is filled in the cavity of the phantom, it was pressed against the Cover Slip by a steel stick of 3 mm diameter first and a fine knife similar to the ones used by Dental Doctors for dental fillings Figure 4.2 and 4.3

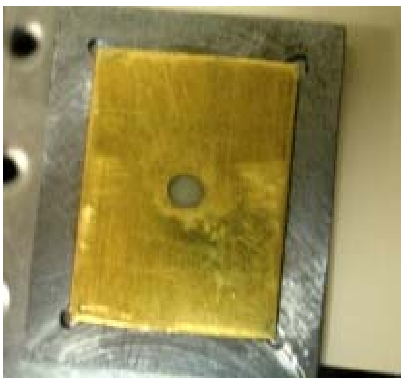


Figure 4.2 Filling of the Cavity

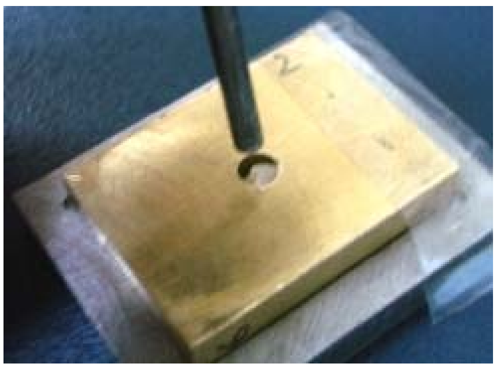


Figure 4.3 Filling of the Cavity

Any excess RC is removed flush to the surface of the phantom with the sharp knife, moving tangent to the upper surface of the phantom. Phantom is securely attached to the mold with a sticky tape to ensure it does not move during exposure.

Light guide was placed with its tip directly in contact and centered with the transparent strip – thus 0.15 mm distance to the RC, enabling even illumination of the working portion of the specimens as well as easy, error free handling.

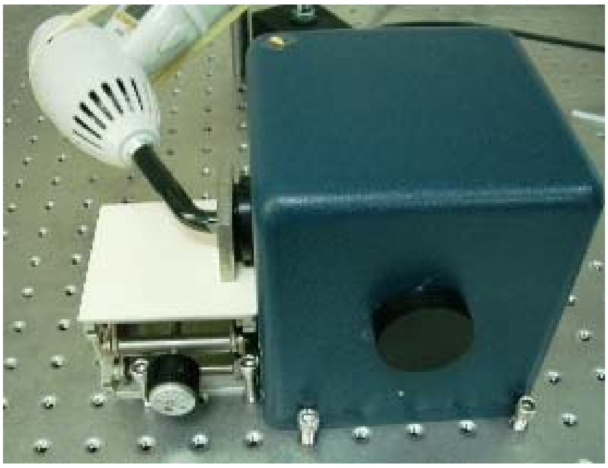


Figure 4.4 Complete LCU and Phantom Setup

Readings were taken and recorded for the below setups:

- Darkness inside the covering box, through the Integrating Sphere (IS), free of LCU and Dental phantoms
- Just LCU through the IS
- LCU unit, through the mold with Cover Slip
- LCU unit, through the 4 mm diameter dental phantom, empty, but with Cover Slip, for phantom thickness of 1 mm to 8 mm

Readings were taken initially with dental phantom empty (free of RC) at each step from 1 mm to 8 mm. Once the phantom was filled with the RC the whole setup was covered with a cardboard box to further reduce any ambient light. Recording was started before turning on the light of the LCU, to record any post or prior ambient or noise factor to deduct from the readings. The data recording continued after the LCU would switch off for a minimum of 5 seconds

Once the recording was over, dental phantom would be removed and polymerization was examined by the scraping method and vernier caliper penetration method modified from ISO 4049 to determine the level of hardening (Figure 4.5)

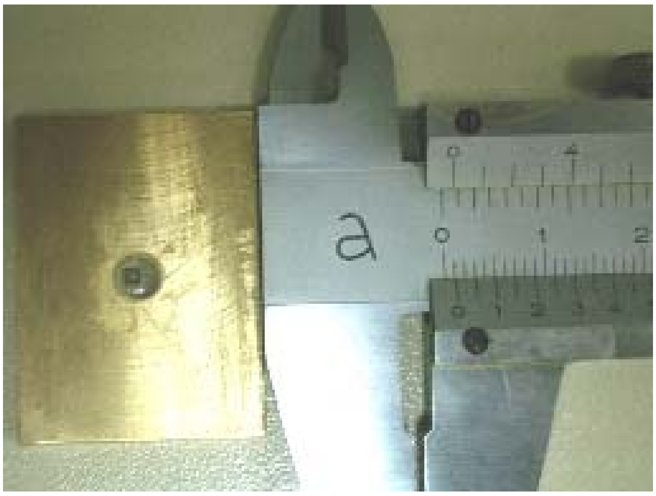


Figure 4.5 Vernier Calipper penetration method for soft RC determination

Once these values were recorded, the sample was locked in a dark enclosure, for further reference.

Instrunet Software is used to record data with these settings:

Sample rate 100 – One sample is taken each miliseconds. Samples per scan 3000 – The total sampling time is limited to 30 seconds for 20 second cure time. Data initially stored in Text Merge format to Ram Buffer and then recorded as text file.

Graph is selected to plot Line. Horisontal displacament is selected bi-polar at 0.5 V maximum range. Data recorded in Slot #100, Through Channel Ch10 Vin +.

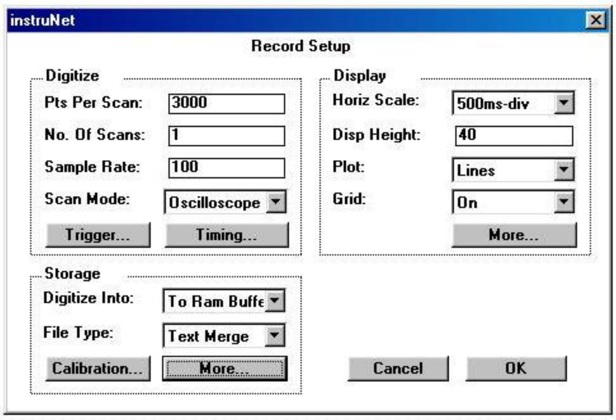


Figure 4.6a Instrunet Setup-1

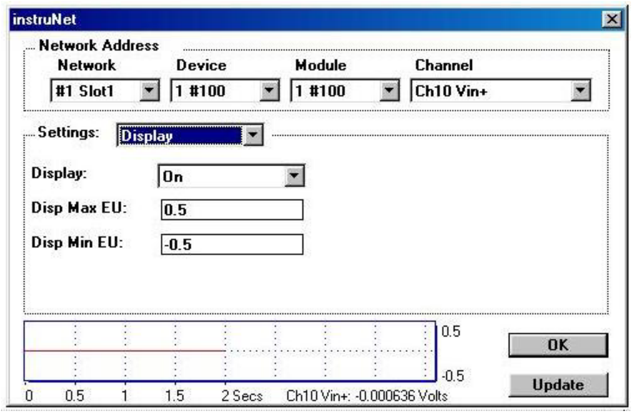


Figure 4.6b Instrunet Setup-2

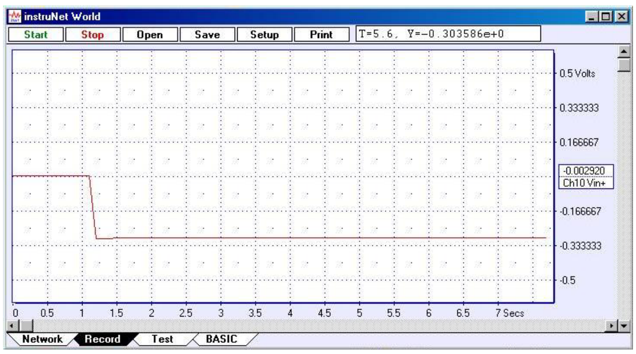


Figure 4.7 Instrunet Setup-3
Recording to be followed realtime onGraphic Screen

5. RESULTS AND DISCUSSION

Below sampling rate and duration is used for all group A experiments:

Sampling rate : 10 milliseconds

Duration : 25 seconds

Measuring range : ± 500 mV

5.1 Darkness

Darkness has been measured using the integrating sphere, covering box, free of LCU and dental phantoms The readings have shown to fluctuate between positive and negative readings As negative light intensity reading is an error, the readings are regarded as bi-polar noise. Maximum values and averages of negative and positive noise levels were:

Maximum positive : 0.80 mV

Maximum negative : -0.72 mV

Average positive : 0.57 mV

Average negative : -0.42 mV

These levels, can be neglected for light intensity measurements behind RC of thickness 1 mmto 6 mm. However for RC of thickness of 7 mm and 8 mm as they are proportional to the magnitude of the actual signal, they cannot be neglected. With the low light intensity values in 7 mm and 8 mm thickness phantoms, it is very difficult to differenciate signal from noise, only a trend can be recognized as the LCU is switched on an off.

5.2 LCU with optical fiber and Cover Slip only

The light output from the LCU through the optical fiber and 0.15 mm Cover Slip is measured with the use of integrating sphere. To centre the optical fiber the steel mold is used.

Data here can be taken as the maximum available light intensity that the LCU can provide through its optical fiber, in a clinical application. The maximum optical intensity that falls on the top surface of the RC, in our experiment is a different value. This is due to the fact that, we have used a circular mask (tooth phantom) that limits the diameter of the circular phantom cavity to 4 mm. This value is recorded in sub-section 5.3.

Data was recorded for a period of 10 seconds The chart shows (Figure 5.1) a 0.43% drop in light intensity from the time the LCU is switched on to the time it was switched off (Table 5.1). This is inline with the manufacturers technical data and is accepted to be due to light intensity change in LED, with LED junction temperature. The LED junction heats up as current passes through it and reduces the light intensity if the temperature is not stabilized. The value is relatively small in comparison to total reading on signal, hence it is neglected in our calculations

Table 5.1 Light intensity of the LCU changes in an application duration of 10 seconds by 0.43 %

Maximum reading	355.22 mV
Minimum reading	353.69 mV
Average	354.11 mV

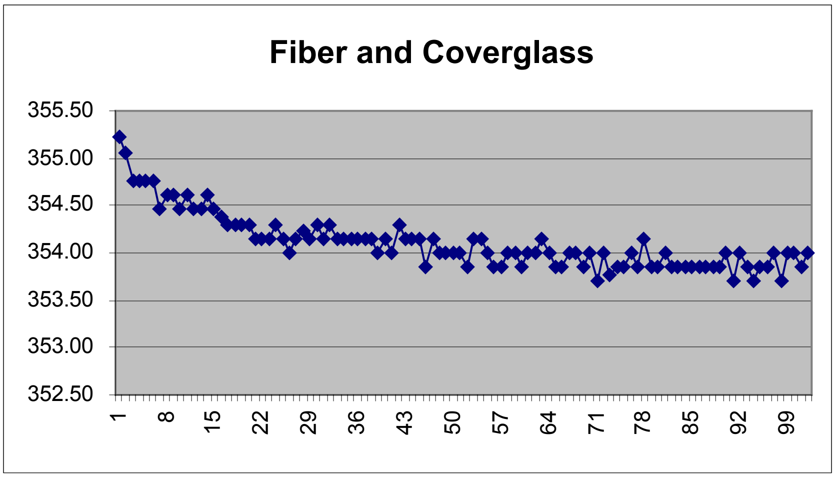


Figure 5.1 Maximum light intensity of the LCU, through optical fibre guide and Cover Slip

5.3 LCU with Phantom and Cover Slip, without RC

The experimental setup is tested for light intensity without he presence of RC, for every 1 mm increment and recorded. Maximum values and averages of negative and positive noise levels for 1 mm phantom without the presence of RC are given in Table 5.2

Table 5.2 1 mm Phantom Light intensity reading without RC

Maximum positive noise (Darkness)	0.94 mV
Maximum negative noise (Darkness)	-0.73 mV
Maximum reading	307.70 mV
Minimum reading	306.18 mV
Average reading	306.60 mV

A linear decline from maximum reading to minimum reading in time is observed also in this trial with 1 mm Phantom. As the noise and difference between maximum and minimum reading are both below %1 of the average reading of light intensity, it is neglected in our calculations.

The average reading of 306.60 mV is taken to represent the light intensity falling on the top surface of the RC. Readings for 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm Phantom are taken. Table5.2 the average of readings recorded for 20 seconds, for each thickness.

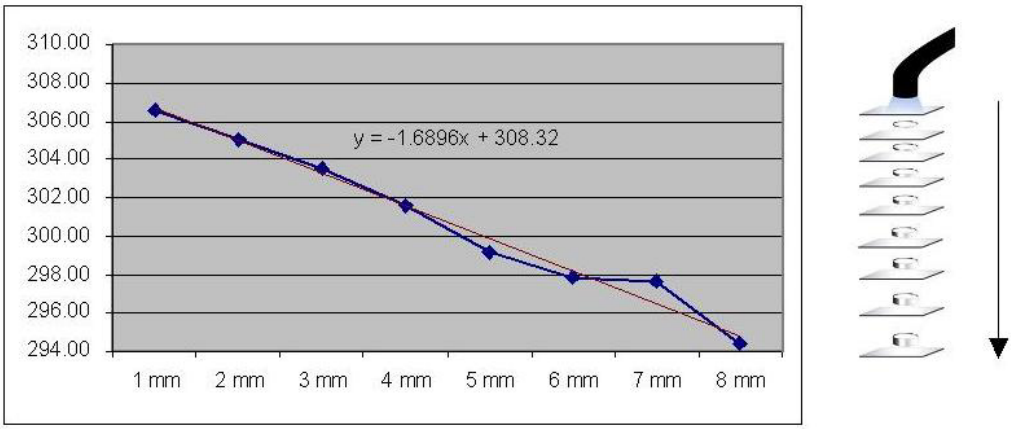


Figure 5.2 Light intensity decreases with every 1 mm increment of dental phantom between the LCU tip and integrating sphere

The Figure 5.2 shows the decrease of light intensity through the dental phantom incremented in 1mm steps. The relationship of light absorption in air is linear. Total loss of light intensity from 1 mm to 8 mm is 4%.

5.4 1 mm Dental Phantom filled with RC exposed with LCU

1 mm Dental Phantom is filled with RC. 8 repetitive experiments have been conducted. All samples showed polymerization on both surfaces, as hardness was tested with scraping and vernier caliper insertion method.

Readings showed an increase of between 3% to 4% increase (average 3.4%) in light intensity from the beginning of exposure to the end of 20 seconds duration. Average slope of the curve is 0.04 (Fig 5.4). This phenomenon has repeated itself with varying degrees in all experiments. Experiments without RC have shown us that LED light intensity has a 0.43% decrease with time due to heating of LED junction. This observation can be explained as the RC increases its optical transparency with the help of polymerization.

Assumption 1: Restorative Composite becomes more transparent to 460 nm light as it polymerizes

The 8 sets of readings as shown in Figure 5.3 average around 237.91 mV. Initial drop poses 24% decrease in light intensity when compared to intensity on the surface.

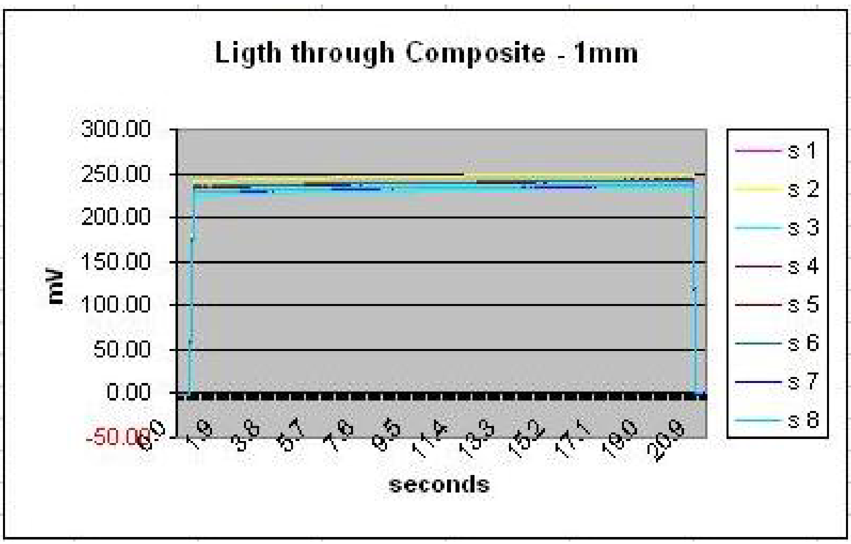


Figure 5.3 1 mm dental phantom with RC polymerization curves

Maximum variability of 6% is observed between trial 2 and trial 3. The maximum variability from mean average value is 4% (Appendix A.- Fig x). Due to the human interference in filling the cavity there have been changes in the total amount of RC observed. Sometimes these were in access of 200 micron.

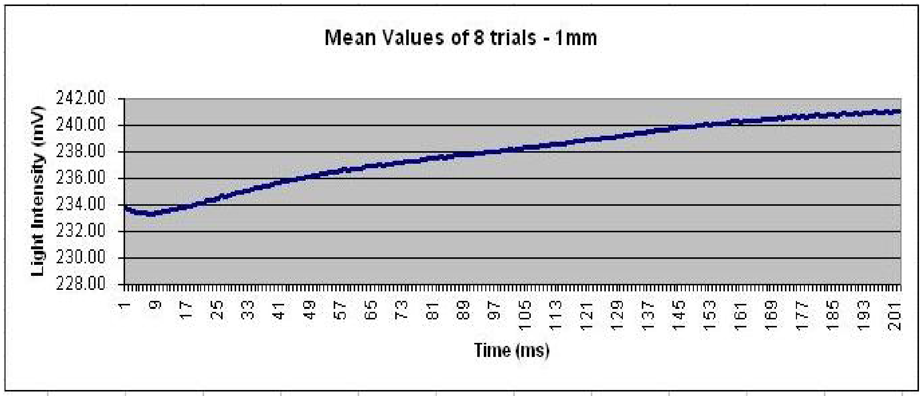


Figure 5.4 1 mm RC polymerization curve (mean values)

5.5 2 mm Dental Phantom filled with RC exposed with LCU

Increase in light intensity with time was between 6% to 7% (average 6.7%). Average slope of the curve is 0.06 (Fig 5.6). All samples showed polymerization on both surfaces, as hardness was tested with scraping and vernier caliper insertion method.

The 8 set of readings as shown in Figure 5.5 average around 192.08 mV. Initial drop poses 20% decrease in light intensity when compared to 1 mm and 39% when compared to the intensity on the surface.

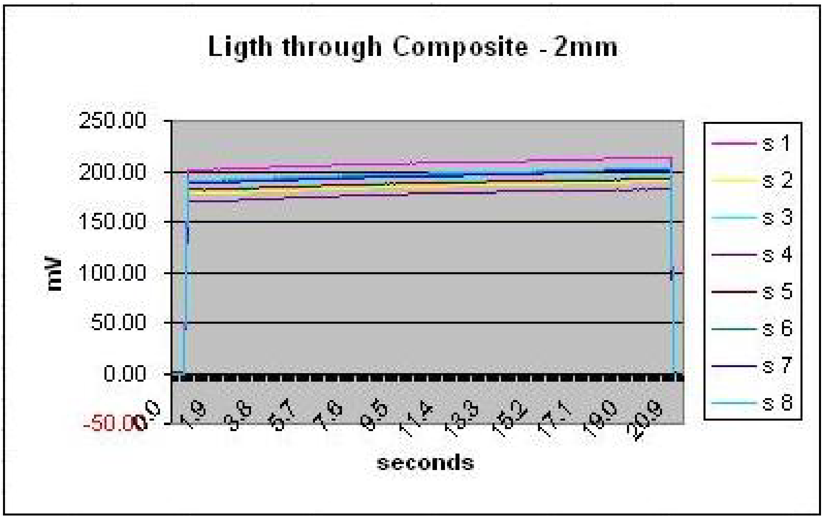


Figure 5.5 2 mm dental phantom with RC polymerization curve

Maximum variability of 15% is observed between trial 1 and trial 4 (Appendix A.- Fig x). The maximum variability from mean average value is 8%.

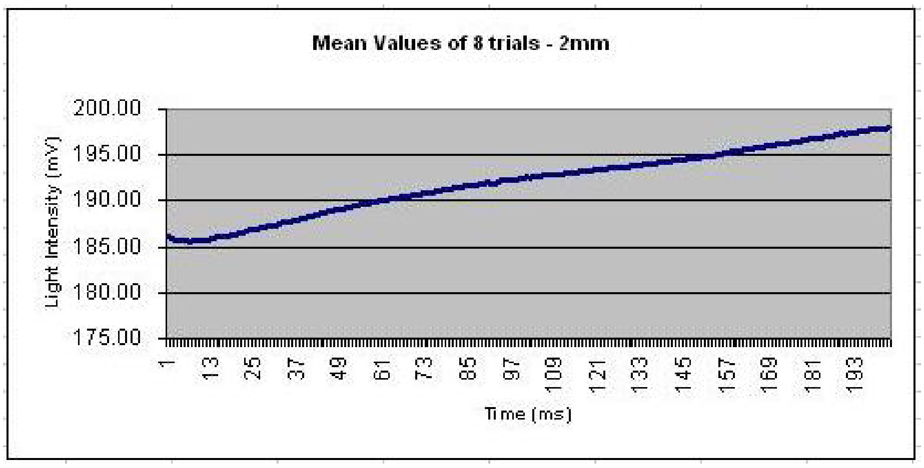


Figure 5.6 2 mm RC polymerization curve (mean values)

5.6 3 mm Dental Phantom filled with RC exposed with LCU

Increase in light intensity with time was between 11% to 21% (average 16%). Average slope of the curve is 0.10 (Fig 5.8). All samples showed polymerization on both surfaces, as hardness was tested with scraping and vernier caliper insertion method.

The 8 set of readings as shown in Figure 5.7 average around 145.80 mV. Initial drop poses 27% decrease in light intensity when compared to 2 mm and 56% when compared to the intensity on the surface.

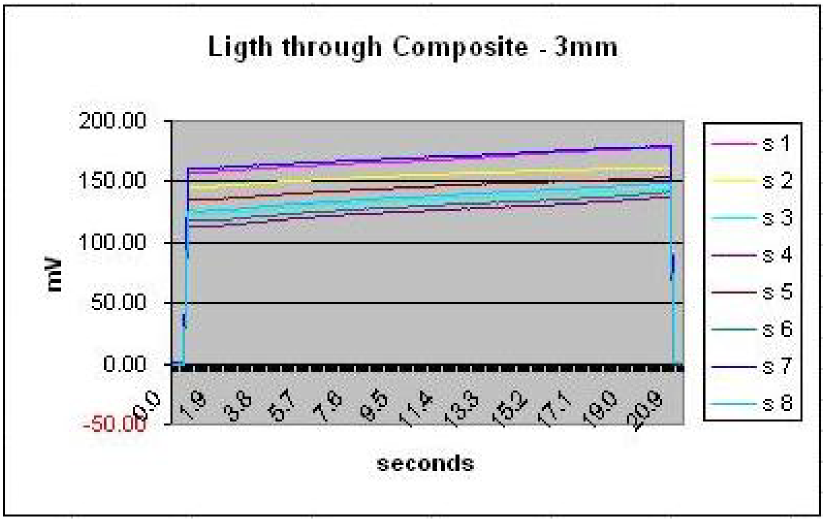


Figure 5.7 3 mm dental phantom with RC polymerization curve

Maximum variability of 30% is observed between trial 4 and trial 7 (Appendix A.- Fig x). The maximum variability from mean average value is 17%.

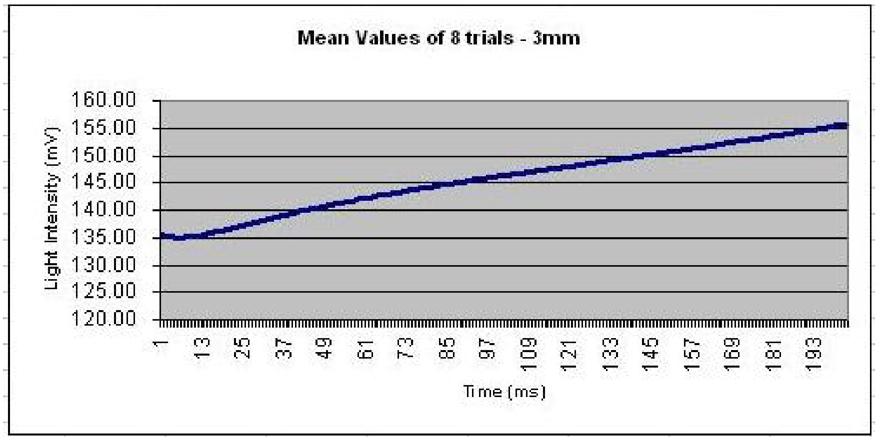


Figure 5.8 3 mm RC polymerization curve (mean values)

5.7 4 mm Dental Phantom filled with RC exposed with LCU

None of the samples fully polymerized on lower surface, as hardness was tested with scraping and vernier caliper insertion method. Hardening depths are given at table 5.3 averaging 3.21mm.

Table 5.3 4 mm Phantom RC Cure depth after 20 seconds

	T1	T2	T3	T4	T5	T6	T7	T8
4mm	3	3	3.2	3.4	3.5	3.1	3.4	3.1

Increase in light intensity with time was between 41% to 84% (average 51.6%). Average slope of the curve is 0.10 (Fig 5.10).

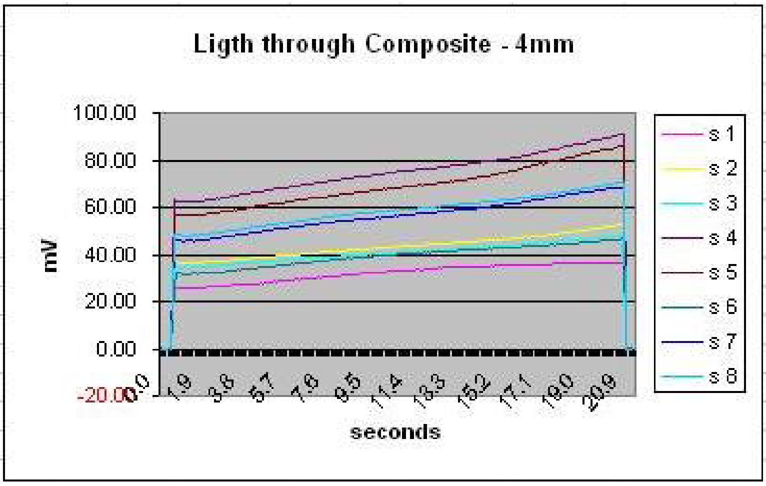


Figure 5.9 4 mm dental phantom with RC polymerization curve

The 8 sets of readings as shown in Figure 5.8 average around 51.87 mV. Initial drop poses 69% decrease in light intensity when compared to 3 mm and 86% when compared to the intensity on the surface. This is the threshold where the light intensity drop increases in exponential fashion rather than the previous linear.

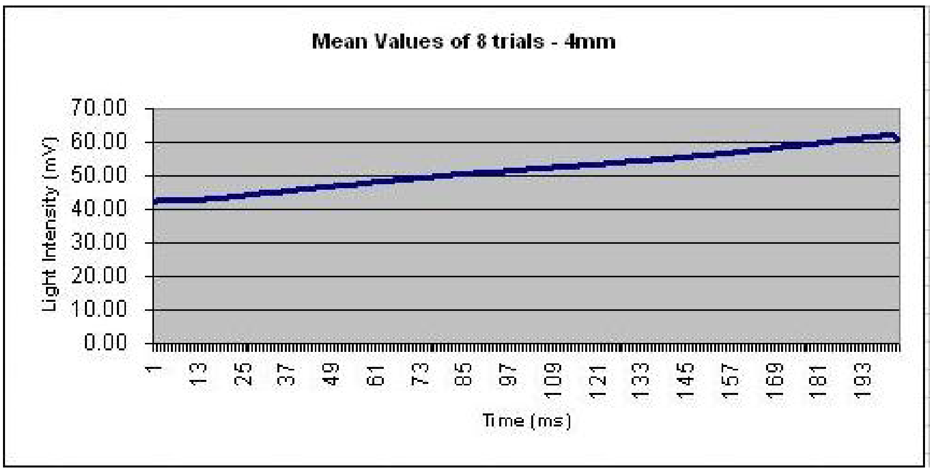


Figure 5.10 4 mm RC polymerization variability

Maximum variability of 52% is observed between trial 4 and trial 6 (Appendix A.- Fig x). The maximum variability from mean average value is 48%.

5.8 5 mm Dental Phantom filled with RC exposed with LCU

None of the samples fully polymerized on lower surface, as hardness was tested with scraping and vernier caliper insertion method. Hardening depths are given at table 5.4 averaging 3.30 mm.

Table 5.4 5 mm Phantom RC Cure depth after 20 seconds

	T1	T2	T3	T4	T5	T6	T7	T8
5mm	3	3	3.3	3.3	3.4	3.3	3.4	3.1

Increase in light intensity with time was between 52% and 74% (average 66.1%). Average slope of the curve is 0.04 (Fig 5.12)

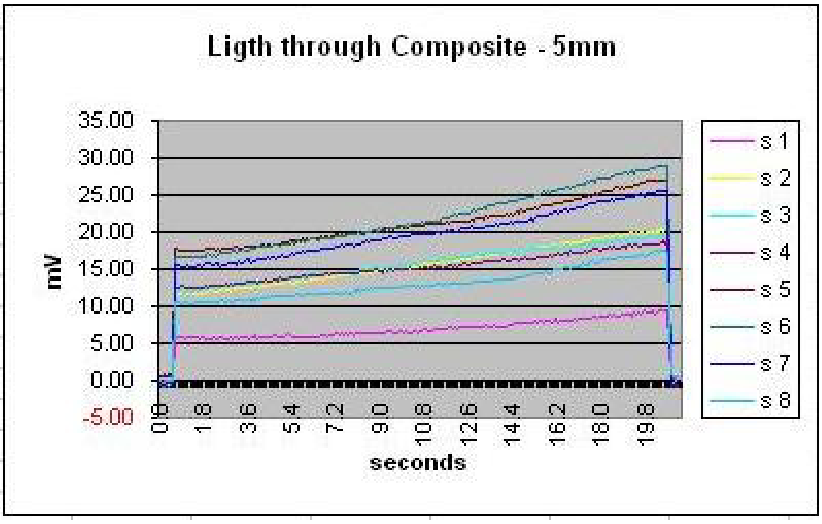


Figure 5.11 5 mm dental phantom with RC polymerization curve

The 8 set of readings as shown in Figure 5.12 average around 16.26 mV. Initial drop poses 70% decrease in light intensity when compared to 4 mm and 96% when compared to the intensity on the surface. Past this point light hardly passes through the composite, only in the 10% region.

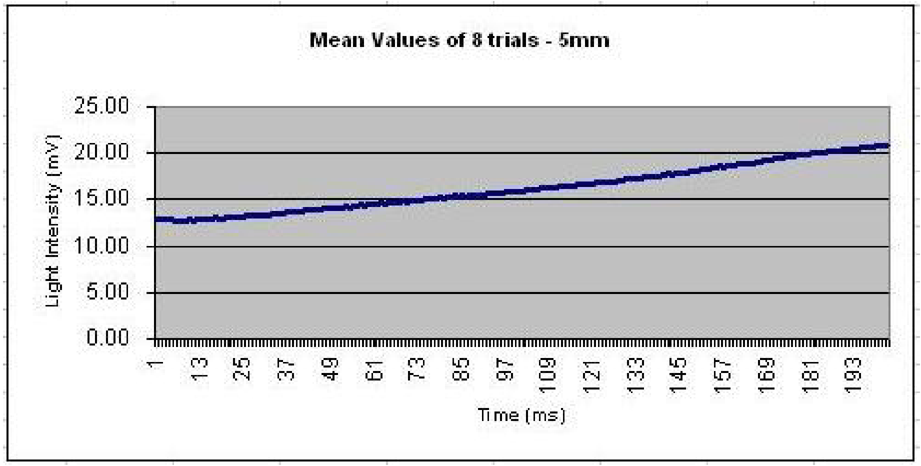


Figure 5.12 5 mm RC polymerization variability

Maximum variability of 119% is observed between trial 1 and trial 5 (Appendix A.- Fig A.5). The maximum variability from mean average value is 57%. The increase in variability is due to the amplitude of the signal getting closer to the noise values Human error is also a factor, but affecting the result less than the case of 1 mm.

5.9 6 mm Dental Phantom filled with RC exposed with LCU

None of the samples fully polymerized on lower surface, as hardness was tested with scraping and vernier caliper insertion method. Hardening depths are given at table 5.5 averaging 3.41mm.

Table 5.5 6 mm Phantom RC Cure depth after 20 seconds

	T1	T2	T3	T4	T5	T6	T7	T8
6mm	3.5	3.5	3.5	3.2	3.5	3.4	3.3	3.4

Increase in light intensity with time was between 52% and 99% (average 72%). Average slope of the curve is 0.01 (Fig 5.14). This again due to the comparable value of the penetrating light prior to polymerization at the upper surfaces and the increment that is released due to polymerization as discussed in earlier sections

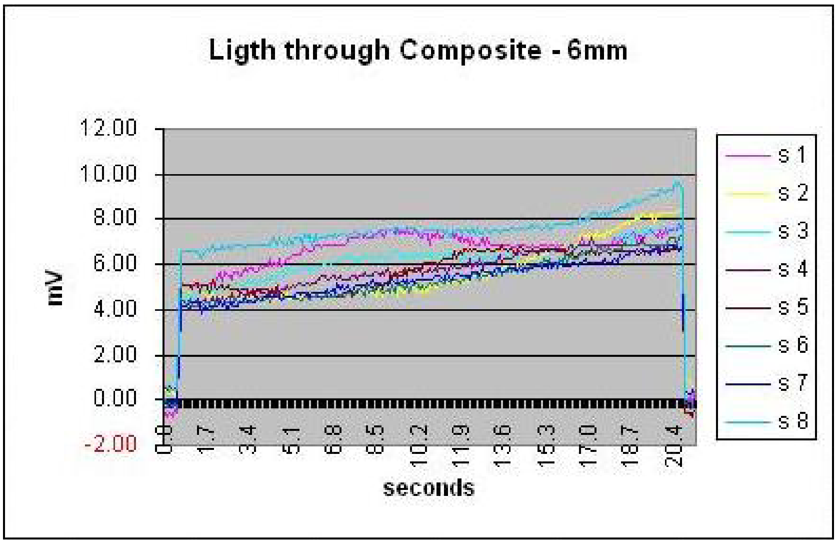


Figure 5.13 6 mm dental phantom with RC polymerization curve

The 8 set of readings as shown in Figure 5.14 average around 6.07 mV. Average slope of the curve is 0.01 (Fig 5.14). Initial drop poses 62% decrease in light intensity when compared to 5 mm and 98% when compared to the intensity on the surface. Still higher than noise value, it is very close making the results of analysis to be less clear and certain.

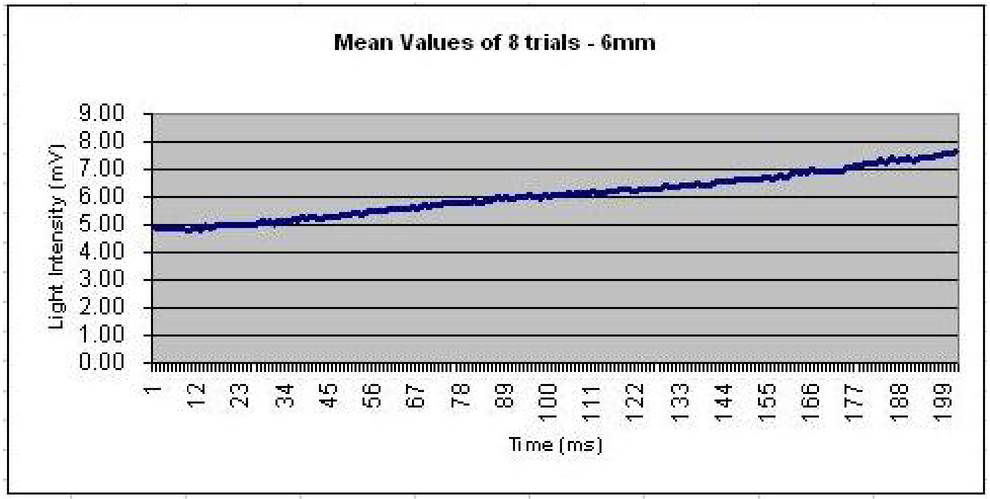


Figure 5.14 6 mm RC polymerization variability

Maximum variability of 41% is observed between trial 7 and trial 8 (Appendix A.- Fig A.6). The maximum variability from mean average value is 25%. The variability as well as any other reading is subject to sceptic evaluation as signal to noise ratio is low after this depth onwards

5.10 7 mm Dental Phantom filled with RC exposed with LCU

None of the samples fully polymerized on lower surface, as hardness was tested with scraping and vernier caliper insertion method. Hardening depths are given at table 5.6 averaging 3.30 mm. With light intensity value dropping below a certain value polymerization seizes

Table 5.6 7 mm Phantom RC Cure depth after 20 seconds

	T1	T2	T3	T4	T5	T6	T7	T8
7mm	3.3	3.3	3.3	3.4	3.1	3.4	3.2	3.4

Increase in light intensity with time was between 59% to 384% (average 171.2%). Figure 5.15. With noise levels relatively high these parameters become insignificant with the slope of the curve averaging 0.00 (Figure 5.16).

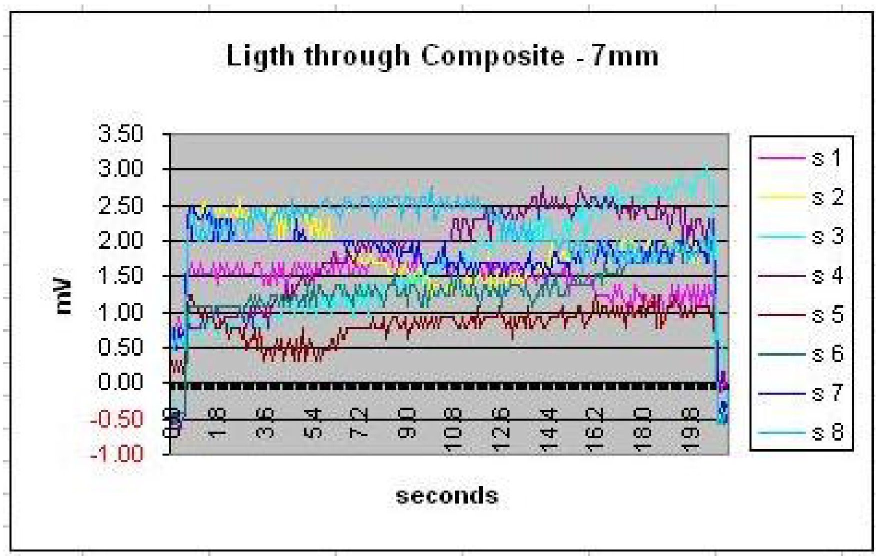


Figure 5.15 7 mm dental phantom with RC polymerization curve

To investigate variability we have changed method from 7 mm onwards; instead of taking the minimum value, which represents the initial light intensity before any polymerization, we have taken maximum value that represents the light through the RC after most of the upper polymerization is established. The reason for this is, low values are so low they give insignificant readings

The 8 sets of readings as shown in Figure 5.15 average around 1.68 mV. Initial drop poses 71% decrease in light intensity when compared to 6 mm and 100% when compared to the intensity on the surface.

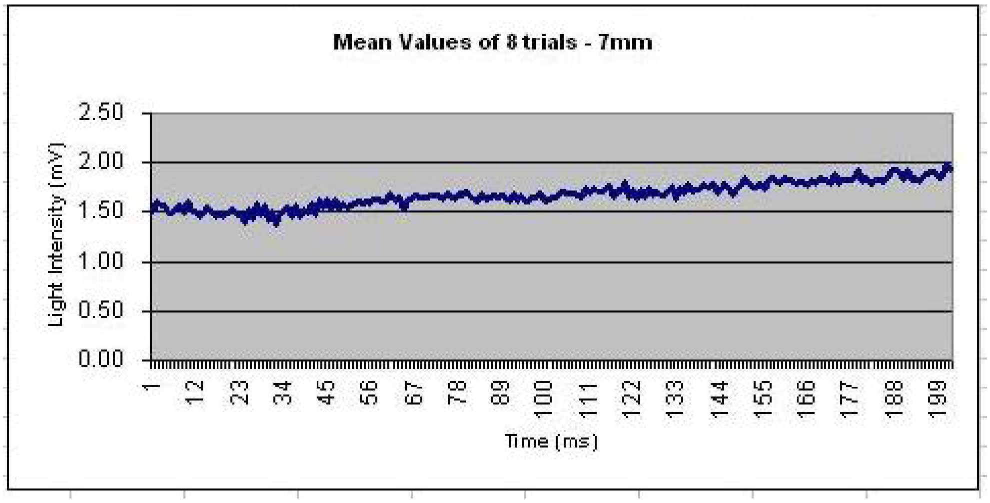


Figure 5.16 7 mm RC polymerization variability

Maximum variability of 49% is observed between trial 3 and trial 5 (Appendix A.- Fig A.7). The maximum variability from mean average value is 49%. This may be a strong indication for Sample 5 to be above the acceptable fault level, as other readings are consistent.

5.11 8 mm Dental Phantom filled with RC exposed with LCU

Polymerization levels did not change in the last two depths tested, with the light penetration diminishing. Hardening depths are given at table 5.7 averaging 3.21mm.

Table 5.7 8 mm Phantom RC Cure depth after 20 seconds

	T1	T2	T3	T4	T5	T6	T7	T8
8mm	3.2	3.2	3.4	3.1	3.1	3.0	3.4	3.3

Increase in light intensity with time was between 247% to 1688% (average 655.8%). Figure 5.17. With these parameters noise makes it impossible to depict a reasonable explanation. Average ramp being 0.00 (Figure 5.18)

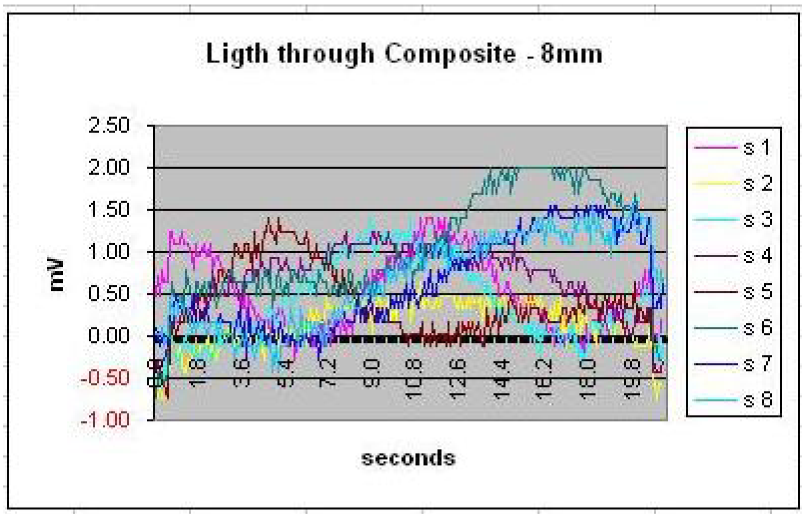


Figure 5.17 8 mm dental phantom with RC polymerization curve

The 8 set of readings as shown in Figure 5.17 average around 1.68 mV. Initial drop poses 83% decrease in light intensity when compared to 7 mm and 100% when compared to the intensity on the surface.

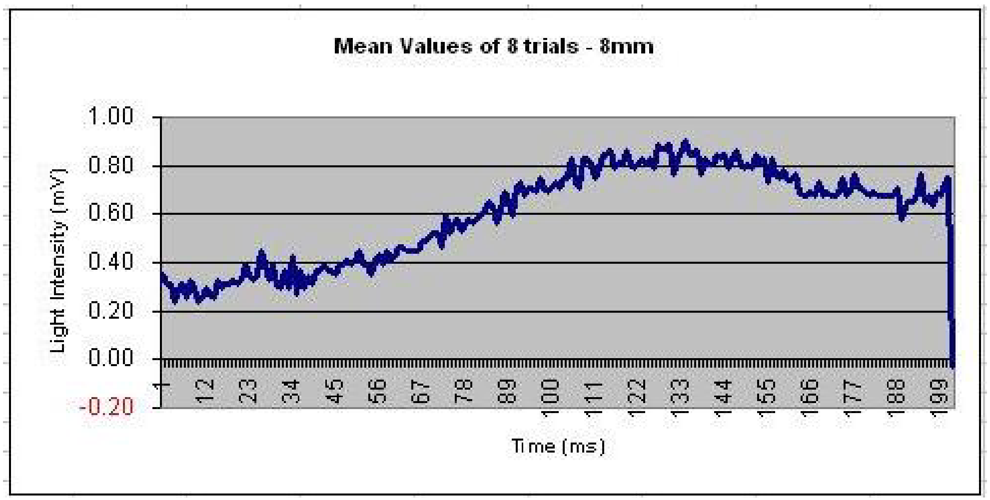


Figure 5.18 8 mm RC polymerization curve (mean values)

Maximum variability of 513% is observed between trial 2 and trial 6 (Appendix A.- Fig A.8). The maximum variability from mean average value is 89%.

5.12 Intensity Change with Depth – Analysis of results

All above results are analyzed to derive a formula of light absorption through composite. To determine the light intensity at each level of composite averages are taken to represent the light intensity.

Table 5.8 Light Absorption by RC depth

Depth	min Intensity	max Intensity	Ave. Intensity	Abs. Drop	Consec. Drop	Remaining Intensity	Cure
0 mm	306.18	307.70	306.60	0	0	100%	
1 mm	233.35	241.06	237.91	24%	24%	76%	ok
2 mm	185.56	197.96	192.08	39%	20%	61%	ok
3 mm	135.01	155.67	145.80	56%	27%	44%	ok
4 mm	42.22	62.47	51.87	86%	69%	14%	3.2 mm
5 mm	12.73	20.87	16.26	96%	70%	4%	3.3 mm
6 mm	4.79	7.62	6.07	98%	62%	2%	3.4 mm
7 mm	1.38	1.99	1.68	100%	71%	0%	3.3 mm
8 mm	0.24	0.90	0.60	100%	83%	0%	3.2 mm

Table 5.8 shows how light intensity decreases with each increment of 1 mm starting from the surface (0 mm).

Light intensity shows a steep drop after 4 mm thickness of RC, carrying only 14% of the intensity at the surface. After that point we have seen that the RC does not polymerize with the durations of 20 seconds. This indicates a threshold value of light intensity existing, where below polymerization cannot find the sufficient energy to take place.

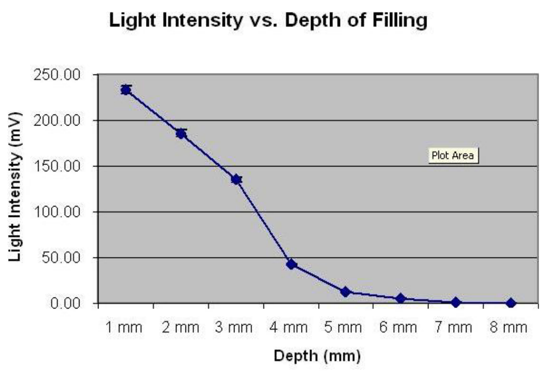


Figure 5.19a 1 to 8 mm Light Levels

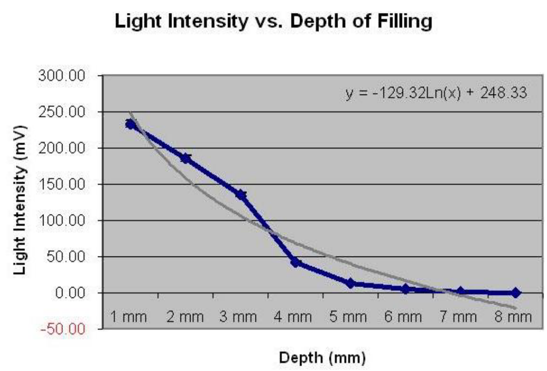


Figure 5.19b Logaritmic function fitted to light levels curve

The curve in Figure 5.19a is the plotting of light intensity at incremental depths of 1 mm. It demonstrates that the light absorption in the RC does not follow a linear relationship. The logarithmic function is fitted on the curve in Figure 5.19b suggests an exponential relationship of a probably a different order.

In the next section a few new questions outside the initial scope of this work, however out of scientific curiosity caused by this work is investigated, with a few unrepeated set of experiments. One is the question of reciprocity of exposure and whether increasing of duration will cause better hardening - as light intensity cannot be increased with the current LCU.

5.13 Investigating polymerization stabilization duration

What needs to be done to achieve single cure polymerization at 8 mm? Obvious next two steps were:

- Increase light intensity
- Increase the duration

If we took 20 seconds of cure duration at maximum light intensity a correct exposure for 1 mm of RC, and would be able to increase our light intensity to compensate the loss in each milimetre, the below results in Table 5.9 can be estimated.

Table 5.9 Compansation of Intensity Loss

Depth		Remain	Compans.	Intensity	Constant Dose (s)
0	mm	100%	0	306	16
1	mm	76%	31%	402	20
2	mm	61%	65%	505	25
3	mm	44%	127%	694	33
4	mm	14%	625%	2,221	92
5	mm	4%	2304%	7,361	293
6	mm	2%	6297%	19,587	784
7	mm	0%	22120%	68,032	2,839
8	mm	0%	129859%	397,902	7,892

The table suggests that the light intensity be increased by the above steps, reaching above 22,000 % of the light intensity we have used, at 8 mm. Consequently, if reciprocity rule is applicable for exposure, increasing the time to above 2,800 seconds for 8 mm. Neither of these figures suggest an applicable approach in practice.

Prior studies of L. Musanje, B.W. Darvell [12] in this area have shown that reciprocity rule does not apply for exposure with RCs, however extending the cure duration had helped increase the depth of polymerization.

Another area to carry on these experiments were the investigation on the increase of light intensity with time, suggesting the RC to become more transparent as it polymerizes. This also could be an indication of full polymerization, on the hypothesis that once the polymerization is complete light intensity change should stop, as the material will reach a stable condition.

To try both of these assumptions Dental phantoms from 1 mm to 4 mm were irradiated for 90 seconds, and 180 seconds was applied for 5 mm to 8 mm.

Longer times may be required based on Table 5.9, however cure times exceeding 3 minutes are hardly viable in a practical clinical situation. Only higher light output devices with ramp up facilities may achieve shorter cure times at deeper cavities Such a prototype does not exist yet with LED technology.

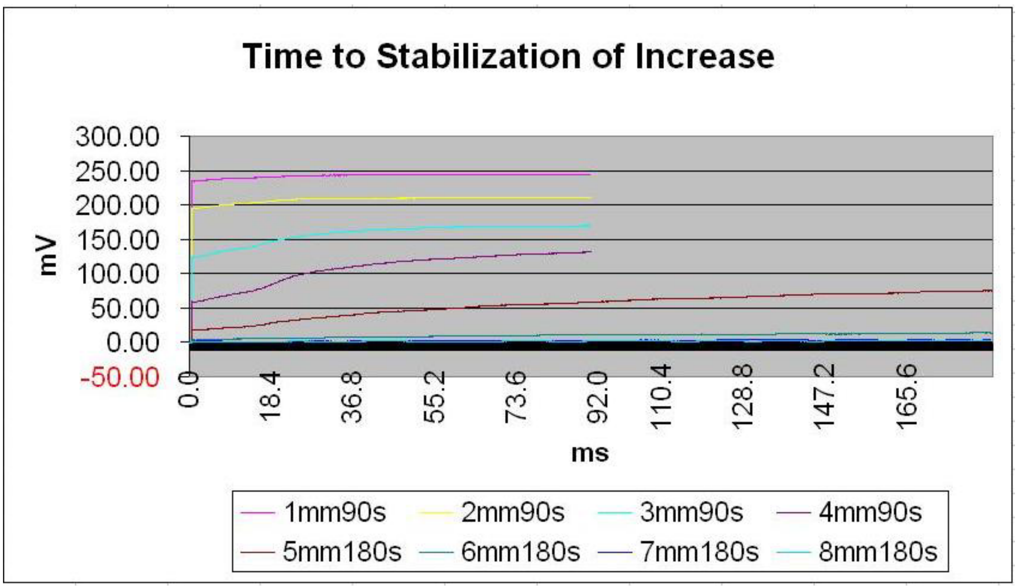


Figure 5.20 1 to 8 mm RC stabilization

Figure 5.20 shows the stabilization curves for the experiments. With a cure time of 90 seconds, 1 mm showed sign of stabilizing (light intensity stopped rising and stayed constant) at 40 seconds 2 mm at the same cure time stabilized at 72 seconds and

3 mm at 84 seconds 4 mm RC did not stabilize at 90 seconds, but was hard when scraping test was applied. Same results achieved for 5 mm and 180 seconds 7 and 8 mm RCs did not stabilize, but yielded above 5 mm hard RC (Table 5.10).

Table 5.10 Stabilization and Cure depths with longer durations

	1mm90s	2mm90s	3mm90s	4mm90s	5mm180s	6mm180s	7mm180s	8mm180s
Stabilize	40.5	71.80	83.90	no	179.9 ?	no	no	no
Cure depth	ok	ok	ok	ok	ok	5.50	5.30	5.70
L.I. by	4%	8%	37%	124%	334%	482%	820%	11712%

6. CONCLUSION AND FUTURE WORKS

Composite polymerization was replicated and observed in laboratory conditions, results were in parallel with ISO 4049 guidelines. Consistent results with low variability have been reached in these experiments (Table 6.1). This is an indication of the method to be an appropriate experimentation. Fluctuations in data can be due to human errors in applying the RC in the phantom, in most parts an error level of 100 micron, where highly possible and difficult to control with hand application, can yield fluctuations of 10%. Automatic filling is possible, but was not practical in this experiment. Deviation was particularly high in 4th and 5th mm depths. This may be due to half polymerization, a transient area.

Table 6.1 Standart deviation of data within repetitions

Depth		Std. Dev	
0	mm		
1	mm	5.0	2.1%
2	mm	9.4	4.9%
3	mm	17.1	11.7%
4	mm	15.3	29.5%
5	mm	4.9	30.2%
6	mm	0.8	14.1%
7	mm	0.6	34.5%
8	mm	0.5	91.2%

Experiments have pointed out to a series of results:

- Light is absorbed as it travels through a RC, the relationship is not linear but exponential. This was parallel with the prior findings of Nomoto R, Asada M, McCabe JF, Hirano S. [25], Chen YC, Ferracane JL, Prahl SA. [22], L. Musanje, B.W. Darvell [11], but contradictory to the findings of Lindberg A, Peutzfeldt A, van Dijken JW. [32], who observed a linear correlation.

- Transparency of the RC to 460nm light increases as it is cured, this is hypothesized as due to polymerization. The increase of light intensity through a certain thickness of RC stops (stabilizes) at some stage, and this is hypothesized as a sing of complete polymerization.
- If the duration of the cure is increased, deeper levels of RC can be cured in one single application at a constant light intensity applied at the surface. The correlation here did not show as linear so, Bunsen-Roscoe law (BRL) of reciprocity is not observed in a linear fashion. It is hypothesized if LCU can increase light intensity in time with a ramp matching the loss in the RC by depth, curing of deep restorations in a single application is not only possible but also time effective.
- Slopes of the curves in Fig. 5.19 indicate that in a single deep restoration application, light increase measured at the bottom of the RC increases more rapidly in deeper applications, thus pointing out to a more effective method when compared to curing composites in 1 mm layers, conventionally.
- 20 seconds recommended duration for 2 mm cure depth is probably not sufficient, as indicated by the stabilization taking place at 40 second for 1 mm and 70 seconds for 2 mm. 40 seconds cure time for 1 mm may be more appropriate.
- Slopes of light intensity increase due to polymerization were linear indicating a linear process (Figure 6.1). The slopes increase until 3 mm and start to decrease after 4 mm. This is in parallel with our tests of hardening material. As material is left not polymerized it absorbs more light and cause a lower increase in slope. The increase in slope with equal increments of thickness until 4 mm, is not linear. This may be an indication of progressive cure, which also will help reduce total cure times.

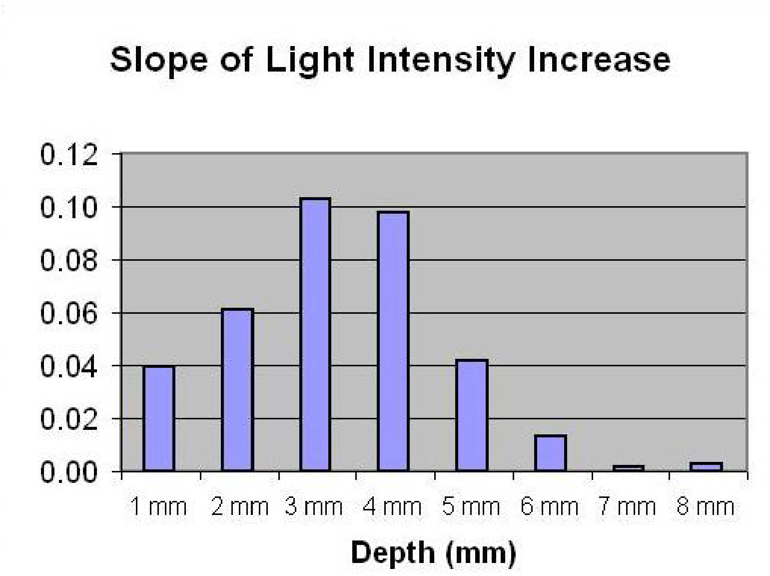


Figure 5.21 1 to 8 mm RC Slope of Light Intensity Increse

Current light intensities of LED based LCU are not sufficient to cure depths of more than 4 mm in a reasonable time frame of 90 seconds, however this may be achieved by ramp controlled higher intensity light source units such as PAC or Argon LASER.

A new series of experiments using special ramp controlled LCU can be a next area of exploration.

To fully polymerize 8 mm thickness of RC it may be hypothesized that a LCU of ten times the light intensity may be required from the Table 5.8. Increasing light intensity alone is not a correct approach based on our findings on stabilization duration of 40 seconds for 1 mm thickness High light intensities prior to polymerization is known to cause shrinkage problems [5] and [27].

Another area that requires further study is the determination of minimum light intensity requirement to polymerize a composite material of 0.5 mm thickness, for 5 s, 10 s and 15 s exposure times However to measure polymerization material test procedures need to be applied, rather than only measuring hardening, which may be misleading.

Low but repetitive occurances of unexpected behaviour on RC is also observed in these experiments, such as the RC expanding after the cure instead of shrinking. This may be due to the properties of the new generation RC incorporating nano-clusters

This phenomenon, if it can be achieved in every application can be useful reversing the affects of shrinkage. The vendor is consulted about this feature, but an answer could not be received prior to printing of this document.

APPENDIX A. VARIABILITY CURVES OF TRIALS 1 TO 8

A.1. Variabilities

This appendix gives the individual light variability values between 8 repetitive recordings, for each 1 mm increment

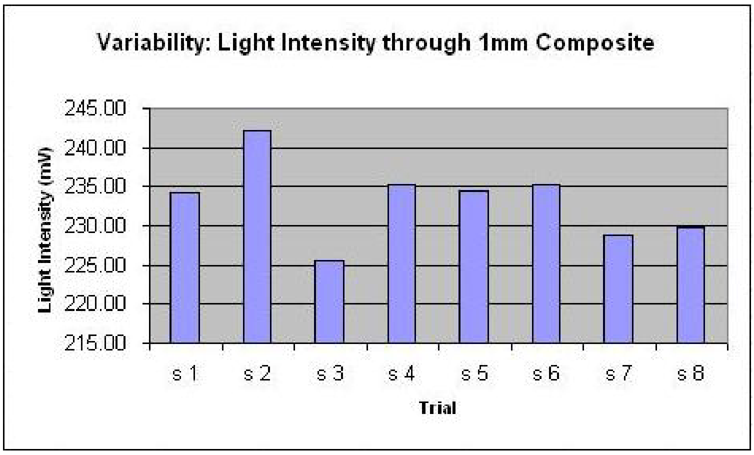


Figure A.1 1 mm Dental Phantom Variability

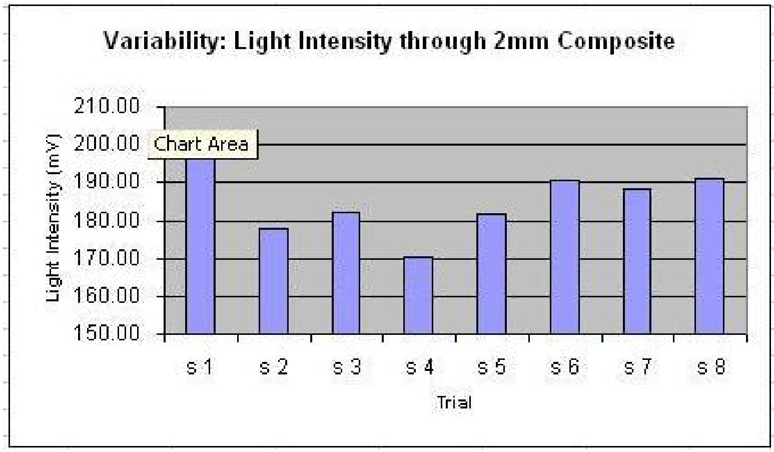


Figure A.2 2 mm Dental Phantom Variability

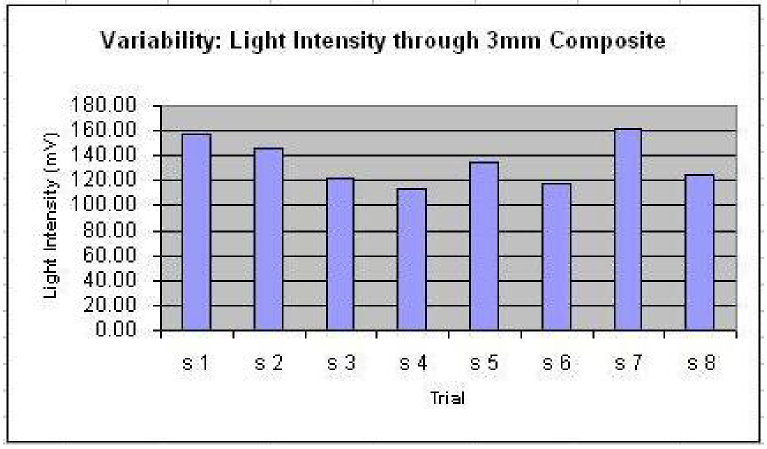


Figure A.3 3 mm Dental Phantom Variability

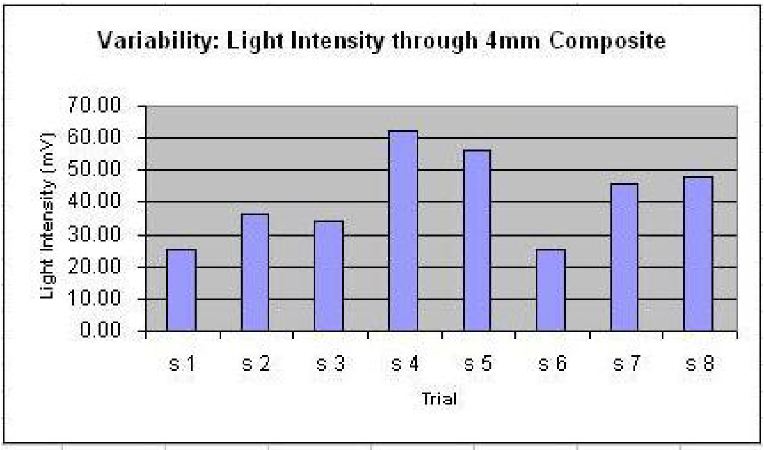


Figure A.4 4 mm Dental Phantom Variability

Figure A.5 5 mm Dental Phantom Variability

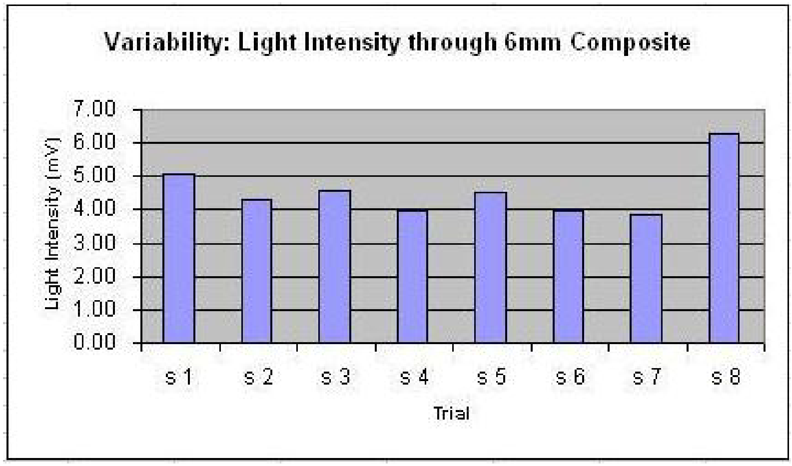


Figure A.6 6 mm Dental Phantom Variability

Figure A.7 7 mm Dental Phantom Variability

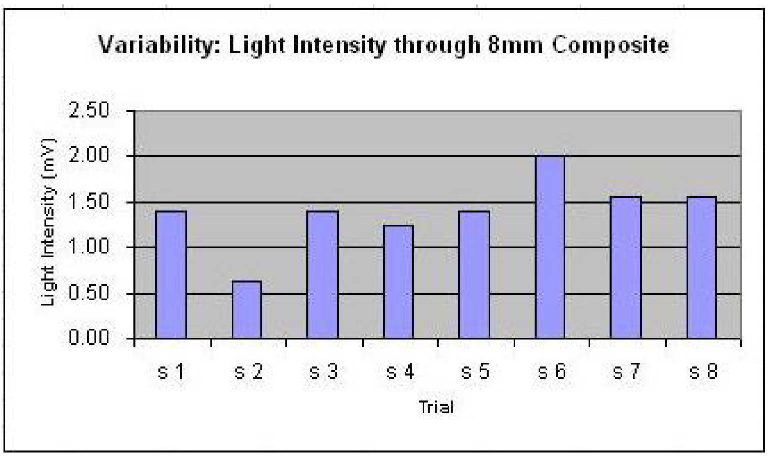


Figure A.8 8 mm Dental Phantom Variability

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