LED TRANSILLUMINATION IN DENTISTRY
PART I: LUMINOUS FLUX OF FIBEROPTIC TRANSILLUMINATORS
PART II: ASSESSMENT OF LED TRANSILLUMINATOR PROPERTIES FOR EVALUATION OF CRACKED TEETH

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Endodontics Department in the School of Dentistry

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ABSTRACT

Nicholas Earl Pettit: LED Transillumination in Dentistry
Part I: Luminous Flux of Fiberoptic Transilluminators
Part II: Assessment of LED Transilluminator Properties for Evaluation of Cracked Teeth
(Under the Direction of Peter Z. Tawil)

The purpose of this experiment was to evaluate the diagnostic test of transillumination. Throughout the literature transillumination is recognized as an important instrument to be utilized in the detection of cracks and fractures of teeth; however, there is no evidence found regarding the ideal specifications of these devices to accomplish this important task. The first part of this study evaluated the tip diameter and luminous flux (lumens) of different types of LED transilluminators, while the second part examined the clinical ability of these devices to detect coronal cracks and fractures in an in vitro model replacing various clinical scenarios. We found a wide variation in the tip diameter and lumens output of the transilluminator devices that were tested and correlated a higher sensitivity in crack detection with increased lumens and tip diameter.

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LIST OF ABBREVIATIONS

DOM	Dental Operating Microscope
LED	Light Emitting Diode
lm	Lumens
MT	Microlux Transilluminator
NI	iPhone Attachment
NL	LED Attachment
NoMag	No Magnification group
QH	Q-Optics Diagnostic Probe HDP
QH2	Q-Optics Diagnostic Probe HDP-02
QM	Q-Optics Microscopic Diagnostic Probe

THESIS INTRODUCTION

Dental practitioners are often challenged with diagnosis and treatment planning of cases involving fractured teeth (1). Many different methods are proposed for these diagnostic efforts including a complete dental history, visual examination, vitality and bite testing, periodontal probing, radiographic examination staining, transillumination, and surgical assessment (2); however, there is no “catch-all” for this problem. Recently, the American Association of Endodontists has claimed that transillumination is “the method that provides the most information, and easily and graphically represents whether a crack is present” (3). The literature has recommended the use of transillumination in the detection of cracks and fractures of teeth as early as the 1970s (4,5).

Transillumination is the “passage of a beam of light through a tooth or other tissue for diagnostic purposes especially in defining fractures” (6), and it is based on the principles of physics. These physical properties include refraction, reflection, absorption, scatter, and others. The basic laws dictate that light will continue to travel in a straight path until it encounters something to change that path; the change that is compelled on light is determined by what type of impediment to its path is encountered. The most relevant laws to transillumination of teeth are those of refraction and reflection. Refraction is the change in direction of light as it passes from one substance density to another; similarly, reflection results in a change of direction of the light at the interface of two mediums, but, in this case, the result is a return of the light through the original substance rather than the continuation of the wave into the second medium. The balance between refraction and reflection is affected by the refractive index, which is given for any substance as “the ratio of the velocity of light in a vacuum (or air) to its velocity in the medium” (7). As the light, or incident ray, encounters a change in medium, the relative differences of the refractive indices of two substances at an interface will determine the direction of the refracted ray and reflected ray in relation to the “normal”, which is a line perpendicular to the interface. There is a “critical angle” for any two substances at, and beyond, where total internal reflection occurs and none of the beam’s energy is transmitted to the second medium; this phenomenon is dependent upon the difference of their refractive indices and is what makes a fracture line obvious for the clinician performing the diagnostic test. A continuous movement of the light around all the tooth surface will maximize angle exposures and will thus enhance the chances of encountering the critical angle to visualize the fracture.

Transillumination of teeth follows these laws to aid in the detection of cracked teeth. Due to the differences of refractive indices of dentin and air (1.5 and 1.0, respectively) (8), rays of light that encounter a crack in a tooth will have their course altered based on the angle of incidence. If the light encounters the crack at the critical angle or greater, no light will continue through the crack, resulting in one part of the tooth being illuminated and the other part remaining dark.

There are many devices currently available commercially that are marketed for the purpose of transillumination in dentistry, and there are many more tools being used off-label for the same intention. Many of these modern devices are utilizing light-emitting diodes (LEDs) as their source of illumination. LEDs have been used for over 100 years, but recent advancements in the technology have resulted in products that are more efficient, cost effective, smaller, and brighter. LEDs are semiconductor light sources designed to emit photons of energy as electrical current is passed through the device; by manipulating the materials chosen for the semiconductor, the energy released can be controlled. The LEDs chosen for transilluminators release energy in the visible light spectrum (~400-700 nm).

The amount of incident light that is transmitted from a transilluminator to a tooth can be measured in a number of ways. Photometry is the measurement of light in relation to a specific detector, the human eye. The photometric principles of luminous flux, luminous intensity, illuminance, and luminance are all part of the function of transillumination. Luminous flux measures the total output of the light source. Luminous intensity measures the luminous flux in a given direction. Illuminance is the intensity of light that is incident on a given surface. Luminance is the amount of light reflected or transmitted by a sample (9).

Many instruments have been used for transillumination in the oral cavity, including commercially available dental transilluminators, the light from the optical fiber of the high speed hand piece, curing lights, and rifle bore lights. However, there is no data regarding the physical and photometric properties of these devices to understand what specifications are optimal for aiding in accurate detection of cracked teeth. This gap in knowledge may result in clinicians misdiagnosing cracked teeth, whether that be missing cracks that are present or visualizing cracks that are not really there at all.

It is important to diagnose cracks accurately, and early, to improve the treatment options and prognosis of the tooth. In a paper published by Krell and Rivera in 2007 (10), it was suggested that cracks identified before causing significant pulpal damage can be treated with a crown and avoid endodontic therapy in almost 80% of cases. Likewise, it is understood that cracks will continue to propagate without proper treatment, which can eventually result in pulpal and periapical pathoses or even tooth loss (11). A recent study which evaluated the width and length of cracks along occlusal surfaces and correlated those findings to the extent of the cracks along the proximal surfaces concluded that these measurements may offer valuable prognostic value for the tooth in question; specifically, longer cracks on occlusal surfaces resulted in longer cracks along the proximal surfaces (12). This again shows that early identification of cracks can result in improved prognosis for the tooth in question.

Despite many recommendations for the use of transillumination in the detection of cracked teeth and many options for transilluminators being available, there is no research regarding the tip diameter or luminous flux that is optimal for accurate diagnosis. The purpose of this thesis was to analyze common transilluminators' tip diameters and luminous flux, and to evaluate their ability to detect cracks clinically through an in vitro model.

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MANUSCRIPT 1: Luminous Flux of Fiberoptic Transilluminators

Introduction

The detection and diagnosis of cracks and fractures in teeth is a constant challenge in dental practice. Accurate identification of cracks is often made difficult by the ambiguity of reported symptoms, the lack of radiographic evidence, existing restorations, and other obstacles (1,2). When early detection and intervention occurs, there is a reduced risk of pulpal involvement, which would subsequently require root canal therapy (3,4) or result in tooth loss. Among various detection techniques for cracks in teeth, transillumination is reported to be the most effective diagnostic test (5). Yet, there is a notable lack of research into the physical characteristics of light sources, i.e., transilluminators, that best enable practitioners to detect cracks and fractures.

Defects that may compromise the integrity and are identified in the coronal tooth structure may be classified as craze line, fractured cusp, cracked tooth, or split tooth (4). Craze lines are nearly ubiquitous in adult teeth and generally non-serious. In these defects, the damage is present only in enamel and is unlikely to spread to dentin, but they can lead to misdiagnosis as more significant longitudinal fractures, which may result in unnecessary treatment. Fractured cusps are most often found with a mesiodistal and faciolingual component, originating at the occlusal surface and extending subgingivally near the cervical margin of the root; these fractures are associated with symptoms from biting forces and cold sensitivity and have a good prognosis if treatment is rendered in a timely manner. Cracked teeth are generally found in the mesiodistal direction with varying extension towards, or onto, the root surface. Symptoms and treatment for cracked teeth are widely variable based on the extent of the crack; the prognosis ranges from questionable to poor. With split tooth being a situation where extraction is often the only treatment option, it is key to diagnose the defect in early stages of development for best prognosis.

Transillumination relies on principles of physics, including reflection and refraction, that dictates the nature with which light will travel through a given medium (6). The path of the light remains constant until it encounters a change in the medium. Thus, when light reaches a crack in a tooth, it interacts with the interface in such a way to alter its path. The change in path often results in a clear definition with one part of the tooth illuminated and the other part dark.

Many transillumination devices are available currently, and they vary greatly one to another in design, cost, and performance. A novel prototype, designed to be very low cost and easy to use, was constructed for the purposes of this study. The aim of this study was to assess the illuminance and instrument tip diameter of common dental fiberoptic LED transilluminators and novel prototypes.

Materials and Methods

A novel prototype transillumination device; the Microlux Diagnostic System (AdDent, Inc., Danbury, CT); and three devices part of the Radiant Lighted Instrument Kit (Q-Optics, Duncanville, TX) were utilized in this study. An exempt status for the study was approved by the University of North Carolina Institutional Review Board of Human Research Ethics, IRB #17-1884.

The novel prototype was constructed to include a fiberoptic cable and an attachment piece to two different light sources - a loupes light (Q-Optics Radiant Headlight System) and an iPhone 8 (Apple Inc., Cupertino, CA). The attachment segments were connected using polyvinyl siloxane impression material applied directly to each source. Before setting of the impression material, a fiber optic cable was inserted to the depth of the LED light source; complete patency of the PVS was verified following the final set by removing the LED light source and visualizing that the cable was unobstructed by any remaining material. A plastic tube to facilitate handling was added to the apparatus near the diagnostic end of the tool (Figure 1). The MicroLux and Q-Optics devices are shown on Figure 2.

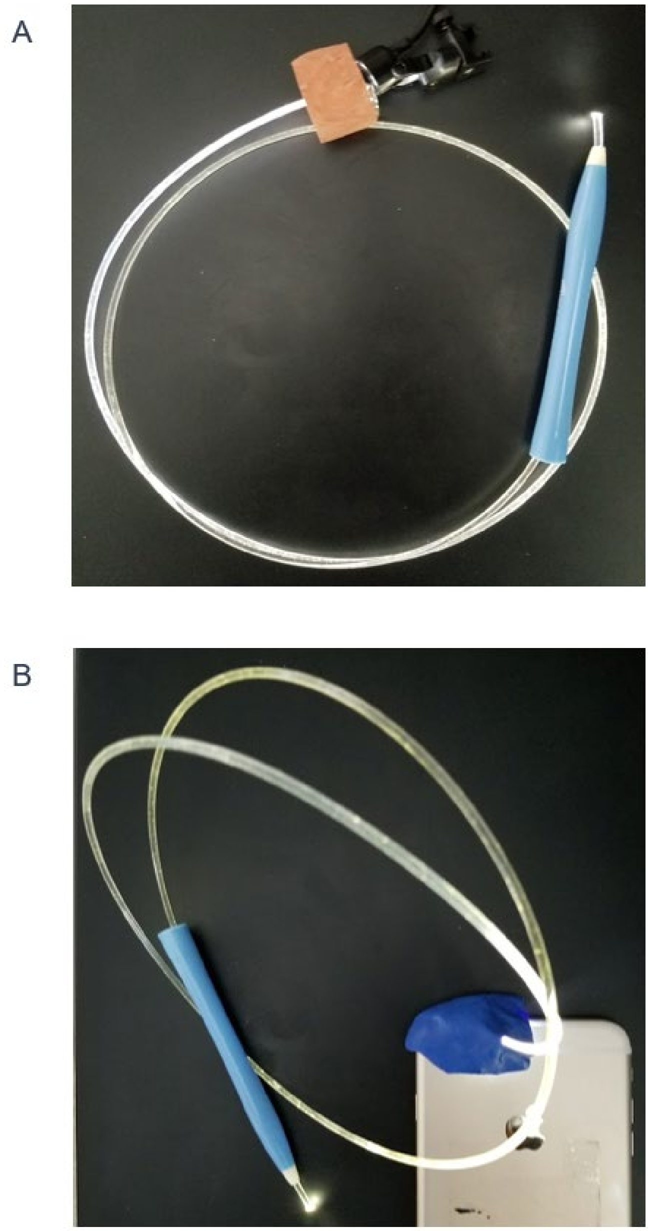

Figure 1: A. Prototype device with attachment for loupes light.
B. Prototype attachment for iPhone.

Three available tip sizes of Q-Optics device (QH, QH2, QM) and the 3mm glass Light Guide of the AdDent device were evaluated. The illuminance of each transilluminator was tested using a digital lux meter (PM6612L Digital Luxmeter, Peakmeter, China) under standardized conditions. All devices were tested in a dark room to block out any ambient lighting. Each unit was placed onto the lens of the digital lux meter, slight changes in angulation of the device were made for five seconds, and the maximum illuminance was recorded. This process was completed ten times for each device, and the means and standard error of the output were calculated. Five devices of each brand were tested to determine inter-device reliability, and each source was tested ten times to account for intra-device error.

The tip of each device, defined as the area that comes into contact with the tooth surface, was measured using an analog caliper, accurate to within 0.001 inch. The size of tips of five devices of each brand were measured and the average diameter for each device was calculated.

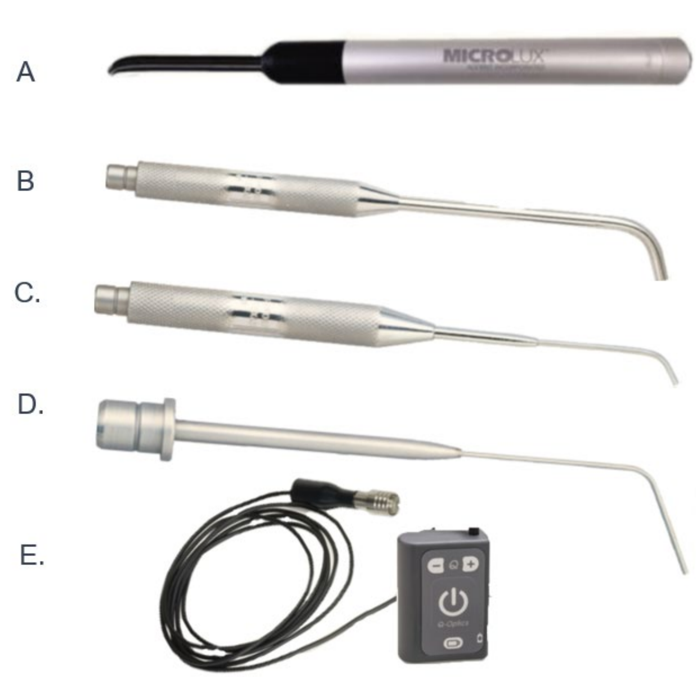

Figure 2: A. Microlux Diagnostic System. B. Q-Optics Diagnostic Probe HDP (QH). C. Q-Optics Diagnostic Probe HDP-02 (QH2). D. Q-Optics Microscopic Diagnostic Probe (QM). E. Radiant Lighted Instrument Kit (Q-Optics).

Results

The tip diameter of the test devices was 0.97 mm (QM), 1.58 mm (QH2), 2.01 mm (NI and NL), 3.06 mm (MT), and 4.76 mm (QH). The mean illuminance (lux) of the test devices was 1247 (NI, 95% CI, 1009-1485); 1739 (NL, 95% CI, 1573-1904); 4874 (QM, 95% CI, 4106-5642); 10333 (MT, 95% CI, 6996-13670); 13712 (QH2, 95% CI, 12028-15395); 68200 (QH, 95% CI, 58550-77849). See Table 1 for additional results.

Table 1: Physical Characteristics of Transilluminator Devices

Device	Tip Diameter (mm)	Mean Illuminance (lux)	Standard Deviation
iPhone Attachment (NI)	2.01	1247	192.2
LED attachment (NL)	2.01	1739	133.4
Q-Optics Microscopic Diagnostic Probe (QM)	0.97	4874	47.4
Microlux Transilluminator (MT)	3.06	10333	126.8
Q-Optics Diagnostic Probe HDP-02 (QH2)	1.58	13712	103.6
Q-Optics Diagnostic Probe HDP (QH)	4.76	68200	397.9

Discussion

The purpose of this study was to assess the physical characteristics of commonly used transillumination devices and to introduce a novel prototype attachment. Our findings showed that there is a significant variation in illuminance and tip diameter of instruments.

The prototype device was designed to improve availability and costs associated with transillumination as these may be obstacles for clinicians in the process of crack detection. By providing an attachment apparatus to nearly ubiquitous light sources such as dental loupes lights and cell phone LEDs, nearly all clinicians are already equipped to allow for instant implementation of such a system into their routine practice. The fiberoptic fiber associated with the prototype allows for greater adaptation of the tooth, including reaching further into interproximal area due to its flexibility and relatively small diameter. The ability to sterilize the device through an autoclave and the low cost associated with the prototype offer additional benefits with this design. However, the illuminance of this device when attached to either the dental loupes light or the iPhone LED was low relative to the other devices inspected. Whether or not the intensity is enough to identify cracked teeth requires further evaluation.

The devices analyzed in this study varied in tip diameter between 0.97 mm to 4.76 mm and produced illuminance levels ranging from 4874 to 68200 lux. These discrepancies between devices may have a significant effect on the ability to accurately diagnose cracked teeth. This data shows that further research is required to assess if this wide variation in transillumination devices can affect its diagnostic sensitivity and specificity.

Conclusions

There is considerable variability in illuminance and tip diameter of commonly used LED transilluminators available on the market. Further research is required to determine the clinical impact of these differences in the identification of cracks and fractures.

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MANUSCRIPT 2: Assessment of LED Transilluminators Properties for Evaluation of Cracked Teeth

Introduction

Cracked teeth are encountered by all dental providers on a regular basis (1), and the diagnosis of these cracks can very often present a significant challenge. The extent of the crack can have wide ranging effect on the treatment recommendation and prognosis of the tooth (2). Many authors have attempted to define or classify cracks in effort to standardize this diagnostic difficulty (3-8). Others have focused on the effectiveness of available diagnostic tests and methods to accurately detect cracked teeth (9-11), including transillumination, bite and vitality tests, staining, periodontal probing, removal of existing restorations, radiographic examination, and surgical assessment. (12-14). Transillumination has been mentioned as an effective method of crack detection from as early as the 1970s (15), and it continues to be recommended as the method of detection offering the most information, and best graphic representation, of cracks well into the 21st century (12).

Transillumination is the "passage of a beam of light through a tooth or other tissue for diagnostic purposes especially in defining fractures" (16). This method relies on the principles of physics, including reflection, refraction, absorption, scatter, and others, which determine light's path through any substance; light will continue to travel through any medium until it interacts with particles contained in that medium or reaches an interface where it passes through to another substance. This principle is easily depicted with light refraction occurring as light passes from air into water. The same principles maintain that light will change its path as it passes through a tooth and encounters a fracture. Changes in the refractive indices between the dentin and fracture line result in refraction and reflection of the light at that interface; at angles greater than the "critical angle", calculated by the difference in refraction indices, total internal reflection will occur, which will result in no light passing beyond the crack. This phenomenon is clinically detectable when teeth with cracks are inspected with a transilluminator and the result is observed as a clear definition between a part of the tooth that is fully illuminated and another part that is relatively dark. The accuracy of transillumination, however, has been challenged in cases with existing restorations and without the aid of magnification (7,9,10) as the introduction of other materials and interfaces will interfere with the transmission of light regardless of the presence or absence of a crack.

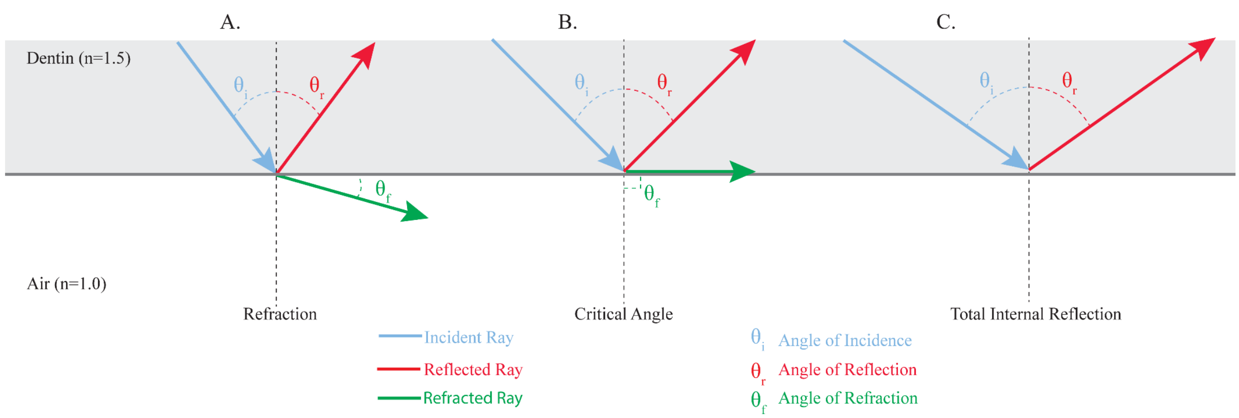

Figure 1: A. Light at fracture line with incident angle less than the critical angle resulting in reflected ray returning through dentin and refracted ray continuing through crack. B. Light at fracture line at critical angle resulting in reflected ray through dentin and refracted ray parallel to the crack line. C. Light at fracture line with incident angle greater than critical angle resulting in total internal reflection.

Commercially there are many devices that are marketed as transilluminators, and, additionally, there are many other devices that are being used as such off-label. These devices differ significantly in design and cost; however, no research has been performed to evaluate the physical characteristics required for accurate diagnosis of cracks. The wide variability of sizes and intensities of transilluminators may result in clinicians mistakenly relying on their device for diagnosis of cracked teeth even if its properties do not produce optimal sensitivity. The aim of this study was to evaluate the ability of three LED-transilluminator devices with different diameter heads (Small - 0.97 mm, Medium - 1.58 mm, Large - 4.56 mm) at varying intensities (L - Low, H - High) to detect cracks in teeth through an in vitro model, in both coronal and endodontic assessments . The effectiveness of magnification on crack detection was also analyzed.

Materials and Methods

Sample Selection

Forty-four posterior teeth (22 molars and 22 premolars) extracted for reasons unrelated to this study were selected for analysis. Twenty-nine of the teeth had existing restorations and/or caries, and 15 of the samples were unrestored and non-carious. Three diagnostic probes with distinct tip sizes (QM – 0.97 mm, QH2 – 1.58 mm, QH – 4.76 mm) from the Radiant Lighted Instrument Kit (Q-Optics, Duncanville, TX) were utilized in this experiment. An exempt status for the study was approved by the Institutional Review Board of Human Research Ethics, IRB #17-1884. Five positive controls were selected that contained cracks that were obvious without any adjunctive diagnostic techniques, and five negative controls were selected where no crack was detected during selection. The “test samples” selected were found to contain cracks only detectable with the aid of magnification and transillumination.

Table 1: Physical Characteristics of Transilluminator Devices

Device Notation	Transilluminator Probe	Intensity Setting	Tip Diameter (mm)	Mean luminous flux (lum)
Small	Q-Optics Microscopic Diagnostic Probe (QM)	Low	0.97	1.1×10^{-3}
		High	0.97	4.5×10^{-3}
Medium	Q-Optics Diagnostic Probe HDP-02 (QH2)	Low	1.58	9.3×10^{-3}
		High	1.58	29×10^{-3}
Large	Q-Optics Diagnostic Probe HDP (QH)	Low	4.76	315×10^{-3}
		High	4.76	1200×10^{-3}

“Silver” Standard for Coronal Assessment

There is not an established gold standard for confirmation of the presence of cracks in teeth; therefore, this experiment utilized a “silver” standard, which was an out of socket examination using high magnification (19.4x) (7) with the aid of Large-High transilluminator to confirm the presence of a crack.

Sample Preparation and Device Masking

Each sample was mounted into a typodont segment (Acadental, Inc, Overland Park, KS) using mounting wax and Poly-Vinyl Siloxane (Aquasil Ultra, Dentsply Sirona, York, PA) to the level of the cemento-enamel junction to simulate a clinical experience during evaluation (see Figure 1). Samples were stored in purified saline (B. Braun Medical Inc., Irvine, CA) to prevent dehydration.

The transilluminators were masked for evaluation by placing the diagnostic probe through silicon straws and injecting PVS impression material to fill the voids. The tip of each device was trimmed to a similar angle and wrapped with insulating tape (see Figure 2).

Coronal Assessment

Each sample was analyzed by two endodontists with 10+ years of experience under standardized conditions. The teeth were assessed using the following settings: a standard overhead dental light (A-dec, Inc, Newberg, OR) with direct vision, the dental operating microscope (Labo America, Inc, Fremont, CA) set to 7.5x with the light intensity set at maximum (80,000 lux), and the dental operating microscope set to 7.5x with the light off and transillumination performed with each of the three diagnostic probes (QM, QH2, QH). Each device was measure at two distinct intensities (L – Low, H – High), which were adjusted by changing the settings on the light source to either the maximum or minimum intensity. A randomized order was generated (www.randomizer.org) for sample assignments. Evaluators were given 20 s to assess each sample under each of the aforementioned conditions, and their diagnoses were recorded for analysis.

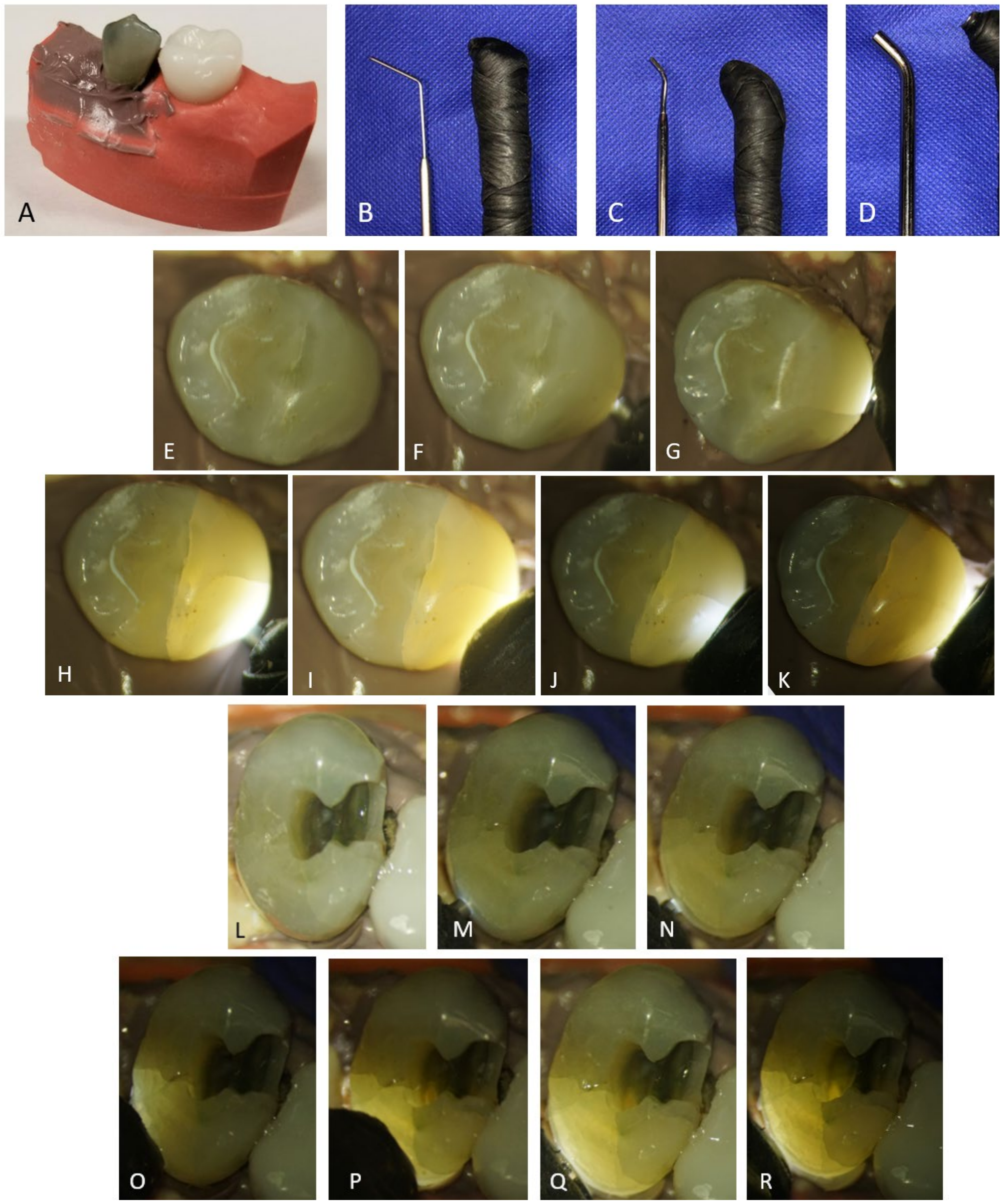

Figure 2: A. Sample tooth mounted for evaluation. B. Q-Optics Microscopic Diagnostic Probe (QM). C. Q-Optics Diagnostic Probe HDP-02 (QH2). D. Q-Optics Diagnostic Probe HDP (QH). E,L. Magnification with DOM. F,M. Small probe at low intensity. G,N. Small probe at high intensity. H,O. Medium probe at low intensity. I,P. Medium probe at high intensity. J,Q. Large probe at low intensity. K,R. Large probe at high intensity.

Endodontic Assessment

Samples remained mounted in the experimental model, and all restorations and/or caries were excavated (10) and endodontics accesses were prepared using a high speed handpiece under water irrigation. The two endodontists again inspected each specimen to evaluate for cracks extending to the internal surfaces of the tooth using the overhead light with no magnification, dental operating microscope (7.5x), and dental operating microscope (7.5x) with each of the diagnostic probes following a randomized examination order.

The teeth were removed atraumatically from the typodont segments and stained with methylene blue dye for final evaluation. Direct inspection of all surfaces of each tooth was completed out of socket using 19.4x and transillumination to confirm the true presence/absence of cracks.

Statistical Analysis

Sensitivity and specificity of each device were calculated for both examiners. Sensitivity of each transilluminator by each examiner were then compared using McNemar's analysis. Level of significance was set at 0.05.

Results

Of the 44 included teeth 39 (89%) were cracked, and 5 (11%) were undamaged (negative control). Sensitivity for each evaluator following each phase of the study are shown in Figure 2. In both parts of the study there is an overall trend for increased sensitivity with increased diameter and luminous flux observed.

In the coronal assessment (see Table 2), the medium-sized light (QH2) exhibited the highest sensitivity by both examiners (82-97%), but these sensitivities were not statistically different from the larger light (QH) at either intensity (77-92%). However, in pairwise comparison the sensitivities of Small-High, Medium-Low, Medium-High, and Large-High were found to be significantly higher than the no magnification (64-77%) or dental operating microscope only (59-77%) groups (see Figure 2).

Evaluation of the samples in the endodontic assessment (see Table 3) demonstrated that the device with the largest diameter (QH) had the highest sensitivity (93-100%). Pairwise comparison showed that Large-High (93-100%) and Large-Low (96%) were statistically superior to Medium-High (82-89%), and Medium-High was statistically more sensitive Medium-Low (71-75%), Small-Low (29-43%), M (50-57%), and NoMag (43%) groups.

Specificity was overall very high for all devices in both the coronal and endodontic assessments. All groups demonstrated a specificity >81%, except for the Large-High group in the endodontic assessment (56.3%).

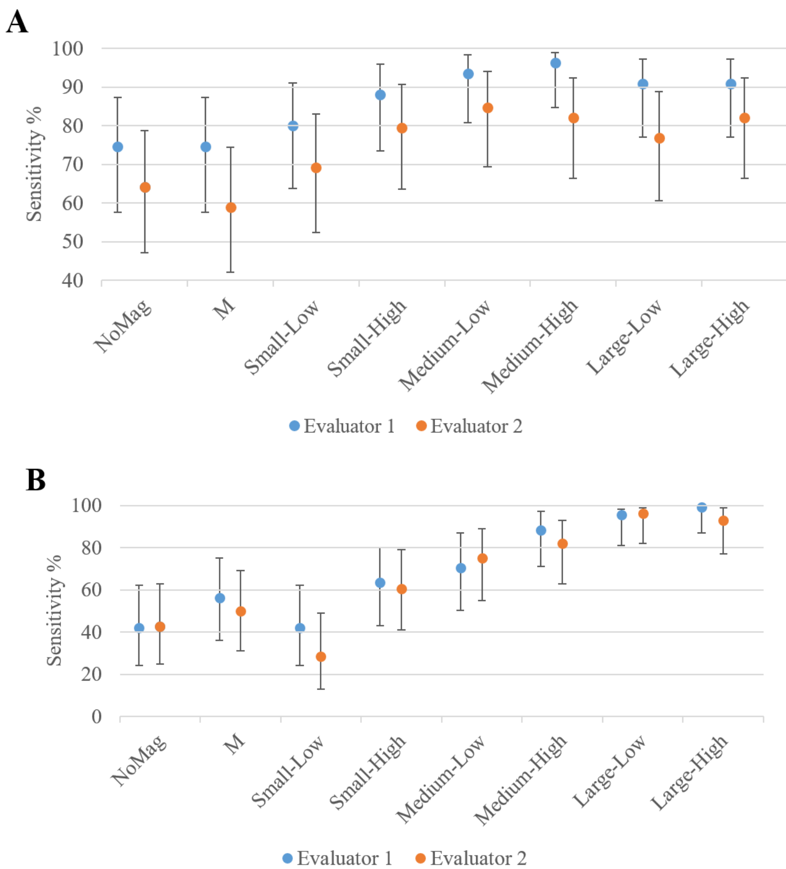

Figure 3: Sensitivity and 95% Confidence Intervals (A) Coronal Assessment (B) Endodontic Assessment.

Table 2. Sensitivity and Specificity of Transilluminators in Coronal Assessment

Examiner 1 Device	Sensitivity %	95% CI	Specificity %	95% CI	McNemar's *P* value
NoMag	76.9	60.7-88.9	100.0	47.8-100.0	**P=0.0039**
M	76.9	60.7-88.9	100.0	47.8-100.0	**P=0.0039**
Small-Low	82.1	66.592.5	100.0	47.9-100.0	**P=0.0082**
Small-High	89.7	75.8-97.1	100.0	47.8-100.0	P=0.125
Medium-Low	94.9	82.7-99.4	80.0	28.4-99.5	P=1.00
Medium-High	97.4	86.5-99.9	80.0	28.4-99.5	P=1.00
Large-Low	92.3	79.1-98.4	100.0	47.8-100.0	P=0.25
Large-High	92.3	79.1-98.4	100.0	47.8-100.0	P=0.25
Examiner 2 **Device**	**Sensitivity %**	**95% CI**	**Specificity %**	**95% CI**	**McNemar's *P* value**
NoMag	64.1	47.2-78.8	100.0	47.8-100.0	**P=0.0001**
M	58.9	42.1-74.4	100.0	47.8-100.0	**P<0.0001**
Small-Low	69.2	52.4-82.9	100.0	47.8-100.0	**P<0.0005**
Small-High	79.5	63.5-90.7	100.0	47.8-100.0	**P=0.0078**
Medium-Low	84.6	69.5-92.5	80.0	28.4-99.5	P=0.125
Medium-High	82.1	66.5-92.5	80.0	28.4-99.5	P=0.0703
Large-Low	76.9	60.7-88.9	100.0	47.8-100.0	**P=0.0039**
Large-High	82.1	66.5-92.5	100.0	47.8-100.0	**P=0.0156**

CI, confidence interval; NoMag, overhead light and no magnification group; M, microscope only group.

Table 3. Sensitivity of Transilluminators in Endodontic Assessment

Examiner 1 **Device**	**Sensitivity %**	**95% CI**	**Specificity %**	**95% CI**	**McNemar's *P* value**
NoMag	42.9	24.5-62.8	93.8	69.8-99.8	**P=0.0003**
M	57.1	37.2-75.5	100.0	79.4-100.0	**P=0.0005**
Small-Low	42.9	24.5-62.8	93.8	69.8-99.8	**P=0.0003**
Small-High	64.3	44.1-81.4	93.8	69.8-99.8	P=0.0117
Medium-Low	71.4	51.3-86.8	87.5	61.7-98.5	P=0.1094
Medium-High	89.3	71.8-97.7	93.8	69.8-99.8	P=0.625
Large-Low	96.4	81.7-99.9	93.8	69.8-99.8	P=1.00
Large-High	100.0	87.7-100.0	56.3	29.9-80.3	**P=0.0156**
Examiner 2 **Device**	**Sensitivity %**	**95% CI**	**Specificity %**	**95% CI**	**McNemar's *P* value**
NoMag	42.9	24.5-62.8	100.0	79.4-100.0	**P<0.0001**
M	50.0	30.7-69.4	100.0	79.4-100.0	**P=0.0001**
Small-Low	28.6	13.2-48.7	93.8	68.8-99.8	**P<0.0001**
Small-High	60.7	40.6-78.5	93.8	69.8-99.8	**P=0.0063**
Medium-Low	75.0	55.1-89.3	81.3	54.3-95.6	P=0.3437
Medium-High	82.1	63.1-93.9	87.5	61.7-98.5	P=0.4531
Large-Low	96.4	81.7-99.9	100.0	79.4-100.0	P=1.00
Large-High	92.9	76.5-99.1	56.3	29.9-80.3	P=0.1797

CI, confidence interval; NoMag, overhead light and no magnification group; M, microscope only group.

Discussion

The aim of this study was to evaluate the ability of three LED-transilluminator devices with different diameter heads at varying intensities to detect cracks in teeth and to analyze the effect of magnification on crack diagnosis. The findings in this study demonstrate that both the amount of light output by a transilluminator and the use of increased magnification during examination affect the ability to detect cracks.

This is the first study that correlates the amount of light output of transilluminators with their sensitivity in tooth crack detection. When using devices with greater light intensity, evaluators exhibited a higher overall sensitivity. It is interesting to note that the smaller diameter and lower output lights (Small-Low, Small-High, Medium-Low, Medium-High) performed significantly poorer in examining for cracks on internal surfaces of the tooth; this may be explained by inadequate intensity to penetrate into the deeper areas of tooth structure.

Increased magnification was shown to increase sensitivity after removal of restorations and/or caries and endodontic access (7). However, this study demonstrates that magnification alone was significantly less sensitive compared to the medium and large transilluminator groups (Medium-Low, Medium-High, Large-Low, Large-High), suggesting that adequate transillumination is an essential adjunct to magnification for accurate evaluation of cracked teeth. Despite a reported 80,000 lux output from the microscope's manufacturer (Labo America, Inc, Fremont, CA), which should be adequate illumination to detect cracks, the microscope itself did not supply light in a uniform direction as is done by a transilluminator. Transillumination requires that the incident ray be primarily in one direction to allow for the physical properties previously discussed to highlight crack lines within teeth. The multi-directional orientation of light coming from the microscope is one possible explanation for increased sensitivity with use of a transillumination device over the microscope alone.

One limitation of this study is that there is not a gold standard for the detection of cracked teeth. Alternative imaging techniques have been proposed, including scanning electron microscopy (17) and Micro computed tomography (Micro-CT) (18), but these also are imperfect.

One inadequacy with both of these methods is that they require the tooth to be extracted for testing, which is not clinically relevant. In addition, the preparation of the samples for scanning electron microscopy is very damaging to the teeth due to the dehydration process required prior to imaging (19), and this process may induce cracks into the teeth and confound the results. Micro-CT, though non-destructive to the examined teeth, may not offer adequate sensitivity to detect microcracks present in the samples (20). Therefore, the “silver” standard was utilized in coronal assessment portion of this study to confirm the presence of cracks in the samples using out of socket evaluation with high magnification and transillumination. Endodontic utilized methylene blue dye as an adjunct to aid transillumination (21, 22) in confirmation of the presence or absence of fracture lines within the samples; unfortunately, this technique could not be utilized in coronal assessment because the dye would have been difficult, or impossible, to remove prior to evaluation of the teeth in Part II (23).

The specificity for all devices, in both coronal and endodontic assessment, were very high (80%-100%), except for Large-High group (56% in endodontic assessment for both examiners independently). Low specificity indicates an increased chance for false negatives, which means that cracks that are present go undetected by transillumination. One possible explanation for this may be that the Large-High device had luminous flux that was too great, enabling the light to mask the presence of a true crack by illuminating beyond the fracture line. This may be an indication to the ideal luminous flux is less than 1.2 lumens; the specificity for the Medium-Low (80-94%) and Large-Low (94-100%) groups were very high while still demonstrating high sensitivity (Medium-High 82-97%, Large-Low 77-96%). Future research should be conducted to evaluate light sources with luminous flux between those of Medium-High and Large-High, .029 and 1.2 lumens, respectively.

Conclusion

Within the limitations of this study, LED transillumination aided significantly in detection of cracked teeth, and sensitivity increased with larger diameter and increased luminous flux; magnification was also found to significantly improve a clinician's ability to diagnose cracked teeth.

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THESIS SUMMARY

Diagnosis of cracked teeth remains a challenging endeavor for dental providers despite frequent encounters with patients suffering from this condition (1). Many diagnostic tests have been recommended for aiding in the detection of cracks, including transillumination, bite tests, removal of restorations, staining, radiographs, wedging, vitality testing, and surgical exploration. Transillumination and complete restoration removal have been reported as being the most useful techniques in visualization of the cracks (2,3,4), and the market is saturated with devices sold specifically as transilluminators for this purpose. However, there is a complete lack of evidence regarding the physical characteristics of these devices, including tip diameter and light output, and their ability to aid in the diagnosis of cracked teeth. In this series of experiments, we sought to evaluate the ability of three LED-transilluminator devices with different diameter heads at varying intensities to detect cracks in teeth and to analyze the effective of magnification on crack diagnosis.

After testing crack detection using the overhead dental light with no magnification, the DOM, and three transilluminator devices at two distinct intensities, we determined that LED transillumination increased the sensitivity of examiners in detection of cracks. There was an obvious trend of increased sensitivity with greater light diameter and luminous flux both before and after removing caries and/or restorations and endodontic access. The largest and brightest lights tested were statistically significantly more sensitive when attempting to diagnose cracks on internal surfaces of teeth following endodontic access; however, using the largest light at the highest intensity resulted in a relatively low specificity, which may result in underdiagnosing cracked teeth.

These results offer the first attempt to correlate physical properties of LED transilluminators to the ability to detect cracks in teeth. It is demonstrated that increasing luminous flux and diameter of transilluminators can increase their sensitivity. Observation with an overhead light or with a DOM alone is not sufficient to detect cracked teeth, and we recommend the use of transillumination in this pursuit. Future studies should look for a limit to the luminous flux which will result in optimal sensitivity and specificity as this experiment described that too much flux can decrease the specificity significantly. All of these findings can help to increase the understanding of physical properties of transilluminators and their effect on accurate diagnosis, which can assist practitioners in hopefully detecting more cracks early in the disease process to increase the prognosis of treatment.

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