Effect of Endodontic Sealers on Dentin Strength

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Effect of Endodontic Sealers on Dentin Strength

Philip Joo-Young Chang

D.M.D., University of Pennsylvania, 2017

A Thesis
Submitted in Partial Fulfillment of the
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Master of Dental Science Thesis

Effect of Endodontic Sealers on Dentin Strength

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Philip J. Chang, D.M.D.
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Abstract

Introduction: The ideal endodontic sealer should be biocompatible, dimensionally stable, and have proper bond strength to dentin. The aim of this study was to apply a hoop stress to sectioned teeth discs which have been obturated with AH Plus sealer with no gutta percha, EndoSequence Bioceramic Sealer (BC Sealer) with no gutta percha, and Tetranite® with no gutta percha until fracture occurred and then compared the failure stresses.

Methods: Teeth were divided into three groups based on the sealer type used. The teeth were sectioned into 2 mm thick discs and load was applied using a piston until fracture took place. The stress generated by the sealer on the dentinal wall was then calculated using a hoop stress formula. One – way ANOVA with a 95% multiple range test was used to compare hoop stresses at failure for all groups (SPSS, TBM). Tukey HSD multiple comparisons test was also implemented to compare values of each group. Linear regression was used to examine failure load versus dentin wall thickness (SigmaPlot 13.0, Systa Software).

Results: Fracture loads forces exerted by the various sealers on the internal tooth wall, demonstrated significant differences amongst all three groups (p < 0.0001). The mean and standard deviation values for failure stress loads were 499.80±120.5555 MPa, 622.3125± 83.7154 MPa, and 708.2357± 68.2772 MPa for the AH Plus sealer with no gutta-percha group, BC sealer with no gutta-percha group, and Tetranite® group respectively. Multiple comparisons showed significant differences between the AH Plus sealer group and BC sealer group (p < 0.002), AH Plus sealer group and Tetranite® group (p < 0.0001), and BC sealer group and Tetranite® group (p < 0.042).

Conclusions: Implementing the hoop stress introduces a novel method for the field of endodontics, of testing sealers and their influence on dentin strength. The current knowledge gap in endodontics lacks a specific method or test application for sealers to potentially enhance dentin strength. The use of piston drive hoop stress test in conjugation with the MTS 858 Mini Bionix® II Biomaterials Testing System is able to provide a method for testing failure stress loads on obturated sectioned teeth. Tetranite® significantly increased fracture stress compared to AH Plus sealer and Endosequence BC sealer. The novel Tetranite group enhanced dentin strength in this study.
I. Introduction

Conventional non-surgical root canal therapy primarily consists of shaping and cleaning with endodontic files and irrigants, then filling the root canal space with gutta-percha and endodontic sealers. There are a myriad of endodontic instruments currently available for shaping and cleaning which mainly includes endodontic hand files, rotary file, reciprocating files, and ultrasonic tips. Endodontic hand files are manually operated endodontic instruments used to mechanically prepare root canals. Hand filing may be much more time consuming and less efficient compared to endodontic rotary file instrumentation (Cheung et al., 2009). The hand filing preparation technique can also possibly lead to iatrogenic errors such as apical blockage, canal transportation, ledging, and zipping (Walton et al., 2002). Due to these inefficiencies, rotary instruments for root canal preparation have been a concentration in the endodontic field. After proper mechanical shaping and irrigation has been done, the therapy is completed with obturation techniques using gutta-percha and an appropriate sealer.

Instrumentation using Endodontic Files

Endodontic instruments play an extremely important role in the ultimate success of endodontic root canal treatment. The success of treatment will rely upon these instruments to clean and shape the root canal system. Rotary endodontic files which are mechanically driven with hand-pieces, have proven to be safer and more efficient over conventional instruments. In addition, rotary instrumentation was found to enhance the ability to collect and remove debris from the root canal system while maintaining better control in the central axis of the canal which may reduce ledging or perforating. In 1892, Oltramare described the first use of rotary devices using fine needles with a rectangular cross-section mounted do dental hand pieces while William H. Rollins developed the first endodontic hand-piece in 1889.

NiTi or nickel-titanium rotary files were initially developed in the 1960s for military purposes.
Eventually NiTi was used for orthodontic wires, dental burs, and rotary files. K-type files were fabricated from NiTi and examined for endodontic use (Serene et al., 1995). NiTi rotary files began appearing in the market in the early 1990s. Rotary NiTi instruments have become very common in its use for cleaning and shaping during root canal procedures with fewer procedural errors and more predictable shaping compared to stainless steel hand files (Hargreaves et al., 2011).

 Currently there are more than 30 NiTi instruments systems on the market which are classified by their cross-sectional design, tapers, and tip configuration. Available rotaries have non cutting tips but some have radial land areas while others use the non-landed design. NiTi rotary instruments are able to flare canals by using either the step-back or the crown-down technique. Nickel-titanium alloy can exist in the austenite and martensite crystal structures. Transitioning from one crystal lattice to the other makes this kind of alloy superelastic, giving it shape memory. Due to its high elasticity, forces between the file and canal wall are reduced during instrumentation. These flexible features allows the NiTi files to have less chances of transporting curved canals compared to stainless steel files. Also, NiTi rotary instrumentation causes less hand fatigue as well as being more time efficient in preparing canals. Despite these advantages, NiTi rotary systems will be much more costly due to its special motor systems as well as the files themselves. In terms of quality of debridement or prognosis, no significance difference was seen with Nickel-titanium instruments compared to hand files (Walton et al., 2002).

 Recently in the past decade, certain additional procedures have been used to improve the mechanical properties of NiTi alloy endodontic files. Machining procedures to the NiTi files include twisting, electrical discharge machining, and specific thermal treatments. Based on several reviews, thermomechanically treated NiTi alloy files have been reported to be more flexible while also improving cyclic fatigue resistance a well as greater angle of deflection at failure compared to the conventional NiTi instruments (Zupanc et al., 2018).
Endodontic Core Material

Conventional non-surgical root canals employ various core materials for endodontic obturation. Gutta-percha is considered the “gold standard” material. The gutta-percha is used as the core material to carry and compact the softer sealer material apically and laterally throughout the root canal system. The name is derived from two words: “getah” meaning gum, and “pertja” which was the name of the tree in Malay language. Long before Gutta-percha was being used in western civilization, Malaysian natives were using it to make knife handles, walking sticks, and various other purposes. As time progressed, Gutta-percha was implemented for underwater seawater cables, surgical splints, surgical instruments, and even golf balls (Prakash et al., 2005).

In 1867, Bowman was the first person to use Gutta-percha for root canal filling. Later in 1942, C.M. Bunn reported the complicated molecular chemistry of Gutta-percha. He explained that the polymer could exist in two different crystalline forms (alpha and beta), and could be interconvertible. The commercially available form is in the beta form while natural Gutta-percha coming directly from the tree is in the alpha form (Combe et al., 2001). Gutta-percha can undergo phase transitions when heated at approximately 115° F (46° C) from the beta to alpha phase. Then, transition to an amorphous phase from a range between 130° to 140° F (54° to 60° C). The Gutta-percha will recrystallize back to the alpha phase when cooled at an extremely slow rate; however, this was found difficult to achieve under normal conditions and would return back to the beta phase. The knowledge of phase transformation is important in various thermoplastic obturation techniques (Goodman et al., 1981). By 1959, Ingle and Levine were the first people to propose standardization of root canal filing material and at their behest, standardized Gutta-percha was introduced to the profession after the 2nd International Conference of Endodontics in Philadelphia (Prakash et al., 2005). Gutta-percha used in dentistry today is generally composed of 20% gutta-percha, 65-80% zinc oxide, and varying combinations of barium sulfate, strontium sulfate, titanium dioxide, fatty acids, plasticizers, and coloring agents (Schilder et al., 2001).
Various manufacturers have added additional ingredients such as calcium hydroxide, chlorhexidine, or iodoform as an antimicrobial to supplement disinfectant properties to the material (Ørstavik et al., 2005).

Gutta-percha can be used as a sealer carrier for various reasons such as being unable to retain moisture. The material is also radiopaque, bacteriostatic, easily sterilized, and can be easily removed from root canal space if necessary (Ørstavik et al., 2005). Additionally, Gutta-percha is incompressible and sensitive to temperature changes which allow it to become brittle and fracture before ductile yield occurs (Friedman et al., 1977).

Gutta-percha along with the sealer can be delivered to the root canal system in various ways. Some examples of obturation techniques include, lateral condensation and continuous wave condensation. Lateral condensation employs the master cone corresponding to the final instrumentation size, taper, and length. After applying sealer to this master cone, it is then carefully inserted into the canal and laterally condensed with endodontic instruments such as finger spreaders and finished with additional accessory cones. Another variation of this technique is called warm lateral condensation. The variance is using a heated warm spreader after the master cone, and then laterally compacting the gutta-percha with accessory cones with spreaders.

Continuous wave technique uses the vertical compaction method of first down-packing core material along with the sealer in the apical portion of the root canal system using a heat source such as System B (SybronEndo, Orange, Calif.). Then, the remaining unfilled portion of the root canal system is backfilled with a thermoplasticized core material using injection devices such as the Obtura (Obtura Spartan, Earth City, Mo.). There are two injection techniques available. As previously mentioned before, a preheated thermoplasticized core material is available such as the Calamus® (Dentsply Tulsa Dental Specialties, Tulsa, Okla.) or Obtura (Obtura Spartan, Earth City, Mo.) filling systems. Another method is the cold injection technique in which a flowable matrix is triturated and injected into the root.
canal system, placing a single master cone. An example of the cold injection material is GuttaFlow® (Coltene Whaledent, Cuyahoga Falls, Ohio) which consists of gutta-percha added to a resin sealer, RoekoSeal.

In addition, carrier-based systems for obturation also exist. Firstly, the carrier-based thermoplasticized technique consists of a warm gutta-percha on plastic carrier and directly delivered into the root canal system. Some examples include ThermaFil® (Dentsply Tulsa Dental Specialties, Tulsa, Okla.) and Soft-Core® (Axis Dental, Coppell, Texas). The Carrier-based sectional system uses a size fitted section of Gutta-percha with sealer, and is inserted into the last apical 4 mm of the root canal. The unfilled canal is then backfilled with thermoplasticized Gutta-percha. One example of the carrier-based sectional material is SimpliFill (Discus Dental, Culver City, Calif.).

Other forms of obturation such as chemoplasticized technique and custom cones are also sometimes used. The chemoplasticized technique uses Gutta-percha already fit into the canal, and then softened by way of chloroform or eucalyptol. Custom cones are similar in which chloroform, eucalyptol, or halothane are used to soften the cone in order to make an impression of irregularly shaped or large root canal systems. Finally, paste fill techniques are used without a core material, which may show lower success rates.

Ultimately, Gutta-percha is an acceptable way to transport sealer into the root canal system. However, the sole core material lacks adherent qualities necessary to entirely seal the root canal. There is controversy over which portion of the obturation is more significant int terms of the tight seal during root canal procedures: the core material versus sealers used. It is known however, that a sealer (cement) is essential and needed for the final seal in root canal systems (Hargreaves et al., 2011).
Endodontic Sealers

Endodontic sealers are applied between the core materials and actual dentinal surfaces to close unfilled voids. These voids are made due to the inability of core materials being able to completely fill root canal systems. The major goals of endodontic sealers are being able to tightly adhere to both core material and dentin while having adequate cohesive strength. Without the ability to tightly seal these spaces, microleakages may occur which in turn can compromise the finished root canal treatment. More modern generations of sealers are being fabricated to enhance their ability to penetrate into dentinal tubules and bond to the dentin and core materials instead of just adhering to these areas.

Sealers have the potential ability to create fluid-tight seals and barriers where core materials cannot reach apically and laterally. The sealer is currently regarded with such importance in root-canal treatment that it is often considered to be even more important than the core obturating material itself (Facer et al., 2005). Studies have also shown that sealers may play a role in the prevention of root fractures. Increased adhesive properties to dentin might lead to greater strength of the restored tooth, which may provide greater resistance to root fracture and clinical longevity of an endodontically treated tooth (Schwartz 2006). Differences in the adhesive properties of endodontic sealers are expected because their interaction with either dentin or root core materials may vary with their chemical composition (Lee et al., 2002).

There have been advancements to delivery systems such as the auto-mix syringes which facilitates the mixing of sealers. These systems have also improved the quality of mixture and in turn, the final product of root canal obturations. A vast variety of sealers exist such as polymer resin-based, silicon-based, zinc oxide eugenol, bio-glass, and glass ionomer materials (American Association of Endodontists. Colleagues for Excellence 2009). Ultimately, sealers are required to maintain cohesive strength among the obturation materials.

In his paper, Grossman describes the ideal properties of a root canal sealer (Grossman et al., 1982):
1. It should be tacky when mixed to provide good adhesion between it and the canal wall when set.

2. It should make a hermetic seal.

3. It should be radiopaque so that it can be visualized on the radiograph.

4. The particles of powder should be very fine so that they can mix easily with liquid.

5. It should not shrink upon setting.

6. It should not discolor tooth structure.

7. It should be bacteriostatic or at least not encourage bacterial growth.

8. It should set slowly.

9. It should be insoluble in tissue fluids.

10. It should be well tolerated by the periapical tissue.

11. It should be soluble in common solvents if it is necessary to remove the root canal filling.

Two commonly used sealers today are epoxy-resin based sealers and bioceramic-based root canal sealers. Epoxy resin-based sealers were first introduced to the field of endodontics by André Schroeder (Schroeder, A 1981). Currently, various modifications to the original formula are widely used for root canal filling procedures (Torabinejad et al., 1979; Wennberg et al., 1980). Epoxy resin-based sealers have excellent physical properties. Its benefits include longer setting time, low solubility, high flow rate, low volumetric polymerization shrinkage, and interfacial adaptation and also are related to covalent bonds between epoxide rings and the exposed amino groups in the collagen network (Versiani MA et al., 2006)(Souza SF et. Al, 2009). Resin-based sealers do not contain zinc oxide eugenol and provides substantial adhesion. Among the clinically available sealers, epoxy-resin based sealers are used as root canal sealers due to their dimensional stability and resistance to resorption.
A commonly used epoxy-resin based sealer named AH-26 was initially manufactured as a single obturation material. AH-26 stands for Aethoxylinharz (ethoxyline base in German), Hexamethylene tetramine, and 26 refers to the test number. AH-26 is a prevalent root canal sealer due to its handling qualities such as good flow, antibacterial effects, low toxicity, sealability to dentin walls, fair working time, and well tolerated by periapical tissues (Limkangwalmongkol et al., 1991). The setting time for AH-26 was found to be 36 to 48 hours at body temperature and 5 – 7 days at room temperature which was relatively slow-setting. Controversy has been made due to the findings that showed AH-26 releasing formaldehyde while setting and how it could possibly be of carcinogenic effect. However, one paper has found that the amount of formaldehyde released during pulpotomies with formocresol and from resin-based root canal fillings are at least 1/40 less than the normal endogenous levels in humans, and they do not pose any health risks (Athanassiadis et. al, 2015). AH Plus (Dentsply DeTrey, Konstanz, Germany), an epoxy-amine resin-based sealer, is the modified formulation of AH-26, and does not release formaldehyde like its previous version. When comparing the sealing ability and apical leakage of AH-26 and AH Plus, there was no statistically significant differences (De Moor et al., 2004). Moreover, based on the chromium release method and procedure, AH-26 and AH Plus have the same degree of cytotoxic effect at 12 and 72 hours (Gorduysus et al., 2014). Compared to AH-26, AH Plus is more radiopaque and has a shorter setting time. With a setting time of approximately 8 hours, AH Plus has better flow and is less soluble than AH-26. Due to its optimum flow, dimensional stability, low solubility and concentration, high resistance, and adequate radiopacity, AH Plus one of the most commonly used sealers today (Pinheiro et al., 2009).

Another commonly used sealer material in the endodontic community is the bioceramic filled sealer which has been available in the past thirty years. Due to their popularity, the use of bioceramic technology dove deep into both the medical and dental fields. Bioceramics are ceramic materials which
include bioactive glass, alumina, glass ceramics, zirconia, hydroxyapatite, and calcium phosphates (Hench et al., 1991). Bioceramic materials may be classified into either bioactive or bioinert substances and are functions of their interaction with surround living tissue (Best et al., 2008). The bioactive materials which include glass and calcium phosphate, interact with surrounding tissues to promote growth of more durable tissues (Koch et al., 2009). On the other hand, bioinert materials include zirconia and alumina, which produce an inconsequential response from surrounding tissues and have no biological or physiological effect (Best et al., 2008). The bioactive portion of the materials are further classified according to their stability as either degradable or non-degradable. Bioceramics are also commonly used for orthopedic treatments which include joint or tissue replacements and metal implant coating in order to improve biocompatibility (Afaf et al., 2016). Porous ceramics, such as calcium phosphate-based materials, have also been implemented for bone graft substitutes (Saikia et al., 2008).

Although calcium phosphate was first used as bioceramic restorative dental cement by LeGeros (LeGeros et al., 1982), the first truly documented use of bioceramic materials as a root canal sealer was two years afterwards. Krell and Wefel compared the efficacy of calcium phosphate cement with Grossman's sealer in extracted teeth, where no significant difference was found between sealers in terms of dentinal tubule occlusion, adhesion, apical occlusion, morphological appearance, or cohesion (Krell et al., 1984). There are two major advantages seen with bioceramic-sealer materials. The first advantage is it's biocompatible qualities which prevents rejection from the surrounding tissues (Koch et al., 2009). The second advantage of this sealer material comes from containing calcium phosphate. This improves the setting properties bioceramics and results in a chemical composition and crystalline structure similar to actual tooth and bone apatite materials (Ginebra et al., 1997), which improves the sealer-to-root dentin bonding. Although the exact mechanism of bioceramic-based sealer is unknown, there have been various theories:

1. Diffusion of the sealer particles into the dentinal tubules (tubular diffusion) to produce
mechanical interlocking bonds (Zhang et al., 2009).

(2) Infiltration of the sealer’s mineral content into the intertubular dentin resulting in the establishment of a mineral infiltration zone produced after denaturing the collagen fibers with a strong alkaline sealer (Han et al., 2011; Atmeh et al., 2012).

(3) Partial reaction of phosphate with calcium silicate hydrogel and calcium hydroxide, produced through the reaction of calcium silicates in the presence of the dentin’s moisture, resulting in the formation of hydroxyapatite along the mineral infiltration zone (Zhang et al., 2009)

A relatively modern calcium silicate-based sealer, EndoSequence Bioceramic Sealer (BC Sealer; Brasseler USA, Savannah, GA), is made of zirconium oxide, calcium silicates, calcium phosphate monobasic, calcium hydroxide, filler, and thickening agents (Al-Haddad et al., 2016). This bioceramic sealer is a premixed and injectable form of the cement paste. Although the setting time of BC sealer was found to be approximately 4 hours, in very dry root canal systems, the setting time had increased to 10 hours. Based on these findings, the EndoSequence BC sealer's setting time was dependent on the moisture within dentinal tubules during root canal treatment. As a result, it was unnecessary to add moisture within the root canal before performing the obturation step (BC; Brasseler USA, Savannah, GA). Endosequence BC sealer has also been proved to have enhanced biocompatibility compared to non-bioceramic sealers. One study, using murine osteoblast precursor cell line (IDG-SW3) was exposed to a wide range of concentrations for each of the sealers for 7 days. Within this study, it was found that the BC sealer had excellent biocompatibility even at high concentrations while seeing enhanced osteoblastic differentiation evidenced by increased DMP-1 expression, robust up-regulation of osteogenic marker gene expression, and superior mineral deposition. Conversely, cell death was detected when Roth and AH Plus were used at concentrations
Tetranite® is an injectable, synthetic biomaterial that claims to be the world's first bioresorbable bone adhesive created by LaunchPad Medical Inc. This biomaterial has shown instant adhesive strength to treat bone fractures and stabilize metal components in compromised bone with less invasive procedures. This novel bone adhesive contains mineral-organic biomaterial based on the product formed by mixing powdered tetracalcium phosphate and phosphoserine in an aqueous medium (Technology: Launchpad Medical). Tetranite® is a self-setting adhesive cement that may cure amorphous solids while forming strong bonds to surfaces like bone and metal implants. Crystalline calcium-phosphoserine and apatite phases are formed through the controlled phase evolution of this biomaterial. As solid phases develop, strength is also gained over time. The qualities of this material in combination with the resistance to fibrous tissue ingress allows Tetranite® to maintain a strong adhesive bond, which enables bone fixation and implant stabilization. Tetranite® is composed of tetracalcium phosphate and phosphoserine powders. These portions are mixed with water to produce the mineral–organic bioresorbable bone adhesive (Kirillova et al., 2018). Currently, Tetranite® is being researched to be implemented as a bone cement for implants and possibly endodontic sealer material. The recommended liquid to powder ratio when mixing Tetranite® powder with water is 0.21 mL g–1 for 20 seconds. A large advantage of Tetranite® is its inherent ability to set and maintain its adhesive character even within aqueous environments. The bone adhesive has a relatively fast setting time of 10 minutes from the start of mixing.

**Tooth Cracks and Fractures**

Fractures and cracks provide a diagnostic and clinical obstacle for dental practitioners. Cracked tooth syndrome was first coined by Cameron, where he found that fractures and cracks are a relatively common occurrence in teeth (Cameron et al., 1964). One study found the rate of patients who were
referred from a general dentist to an endodontist with cracks involving marginal ridges to be 9.7% over a six-year period (Krell et al., 2007). There are various types of cracks and fractures seen in teeth which make its absolutely necessary to properly diagnose each situation. The term longitudinal fracture is implemented due to its representation of vertical extensions of fractures which occur over distance and time. These linear fractures have the potential to grow and change. Cracks may be difficult to diagnose due its variety of symptoms, including erratic pain while chewing, response to temperature change, and possible pain when releasing after biting pressure. Cracks that approximate the pulp or periodontium may also cause problems due to the potential of bacterial inflammation. Despite some fractures only being enamel craze lines which are superficial, others may be much more consequential. The Fall/Winter 1997 AAE Colleagues for Excellence article defined 5 types of tooth cracks which included craze lines, fractured cusp, cracked tooth, split tooth, and vertical root fracture.

Craze lines only affect the enamel and have the least negative consequences out of the five classifications of longitudinal tooth fractures. Common in adult teeth, posterior teeth with craze lines are usually seen crossing the marginal ridge, extending down the buccal and lingual surfaces. Anterior teeth show vertical craze lines. Pain is not felt with craze lines because of their sole involvement with the enamel. Although craze lines can be confused with cracks, they can be differentiated by transillumination (Hargreaves et al., 2011). When the tooth is cracked, light will be blocked and only a portion of the tooth structure will light up. However, in the case of craze lines, the whole tooth structure will illuminate (Colleagues Excellence - American Association of Endodontists, 2017).

Fractured cusps are another category of longitudinal fractures that include complete or incomplete fractures, which start coronally and extend subgingivally towards mesiodistal and buccolinguinal portions of the tooth. These types of fractures include at least two parts of the cusp by crossing the marginal ridge and simultaneously extending down the buccal or lingual groove. Fractured cusps will extend to the cervical third of either the root or crown. The affected tooth is treated based on
how much tooth structure is left. The affected cusp is removed and restored with a direct or cuspal-reinforced restoration, such as a full crown or only that covers the entire crack margin. Dentin and enamel bonding with adhesive resins were shown to strengthen the cusps. Endodontic treatment such as a conventional root canal or vital pulp therapy is only needed if the crack involves the pulp chamber or has caused a diagnosis of irreversible pulpitis (Colleagues Excellence - American Association of Endodontists, 2017).

The third class of fractures is called the cracked tooth. Cracked teeth are defined as incomplete fractures starting from the crown and extending subgingivally in the mesiodistal direction. Fractures may extend through either or both marginal ridges and through the proximal surfaces as well. The fracture itself is solely located in the coronal aspect of the tooth or may also extend from the crown into the proximal root (Hargreaves et al., 2011). Cracked teeth can also be labeled as incomplete (greenstick) fractures. Occlusal cracks from cracked teeth are more centered and apical than fractured cusps; therefore, cracked teeth are more likely to cause pulpal and periapical pathosis as it extends into the apical aspect (Colleagues Excellence - American Association of Endodontists, 2017). The wedging test can be used to differentiate cracked teeth from fractured cusps or split teeth. If no movement is seen after using wedging forces, the proper diagnosis would be cracked teeth. Cracked teeth are treated depending on the location and extent of the crack which is sometimes difficult to determine. Extensive cracks of long duration are more likely needed to be endodontically treated, but minor cracks will sometimes need root canal treatment as well. The long-term prognosis of cracked teeth are better if cracks do not extend into the chamber floor. However, patients should be advised that cracks may continue to develop and eventually separate. In 2006, one study showed that root-filled cracked teeth that had a diagnosis of irreversible pulpitis showed a two-year survival rate of 85.5% (Tan et al., 2006). Another study in 2007 evaluated teeth diagnosed with reversible pulpitis and shown to be a cracked tooth. After placement of crown restoration without performing root canal treatment, only 20%
eventually converted to irreversible pulpitis or necrosis over a six-year period (Krell et al., 2007).

Split tooth is another classification of longitudinal fractures that develops a complete fracture which starts from the crown and extends subgingivally towards the mesiodistal direction. The fracture will go through both marginal ridges and the proximal surfaces. Split tooth fractures are located coronally and extends to the proximal root (Hargreaves et al., 2011). Cracks of this category are more centered occlusally and will tend to develop apically. Split teeth are the eventual result of a cracked tooth. As the crack develops, the fracture becomes complete and extends to surfaces in all areas. Root surfaces are also involved in the middle or apical third which usually extend lingually. All dentinal connections are severed and tooth segments are completely separated. Split teeth may occur suddenly but will more likely happen from long-term growth of an incomplete cracked tooth (Colleagues Excellence - American Association of Endodontists, 2017). Although split teeth cannot be saved in its intact form, the position and extent of the crack will determine the prognosis and treatment plan. If the fracture is severe and goes deep apically, extraction is the proper treatment. However, if the fracture is more cervical, there is a greater possibility of survival if the smaller mobile segment is removed.

A “true” vertical root fracture occurs when a complete or incomplete fracture starts from the root and develops buccolingually. Fractures may extend coronally towards the cervical periodontal attachment. Vertical root fractures may involve one or both proximal surfaces (buccal and/or lingual). The length of the fracture may occur as a shorter crack at any level of the root and may not even extend at the buccal or lingual surfaces. However, vertical root fractures commonly extends into the pulp and periodontium while being more centered in the tooth. Patients with vertical root fractures usually present with minimal signs until periapical pathosis occurs. These fractures may mimic periodontal disease or failed root canal treatments, therefore, it is extremely hard to diagnose and may need a referral to an endodontist or periodontist. Almost all vertical root fractures have a history of root canal treatment. When these fractures occur to endodontically treated teeth, the prognosis becomes poor
whether the fracture is detected or not (Saw et al., 1995). Endodontically treated teeth may have a higher potential to cause these fractures due to stress on the canal surface. These stresses may enhance pre-existing surface cracks that were caused by apical force applied to the gutta-percha and could result in circumferential tensile stress (Chai et al., 2012). Other factors that could cause vertical root fractures are occlusal forces and pin and post placement (Saw et al., 1995). Most fractures will display deep probing depths in narrow or rectangular patterns but some may show normal probings. In a 2016 retrospective cohort study, clinical findings most frequently observed in these fractures were pain on percussion (60%), pain on palpation (62%), presence of a deep narrow pocket (81%), and sinus tract/swelling (67%) while “halo”- (J-shaped) type radiolucency (48.7%) was the most common radiographic feature. The most frequently affected teeth were mandibular molars (34%) and maxillary premolars (22.8%) (PradeepKumar et al., 2016). Predictable treatment of vertical root fractures is to remove the fractured root or extract the tooth. Root amputation or a hemisection are also options for multirooted teeth (Colleagues Excellence - American Association of Endodontists, 2017).

**Fracture Models using Hoop Stress and Thick-Walled Cylinders**

Sectioned circular tooth roots may be categorized as a thick-walled cylinder. Thick-walled cylinder with open ends may be loaded by both internal and external pressure. The circumferential stress otherwise known as the “hoop stress” may act through the entire thickness of a cylindrically shaped object due to the difference between the internal and external pressure (Nave et al., 2011). The hoop stress defines a stress distribution with rotational symmetry. For example, hoop stress may be the tension applied to iron bands or hoops of a wooden barrel. Therefore, the force coming from a hoop stress is exerted circumferentially (perpendicular to the axis and radius of the object) in both directions on every portion of the cylinder wall. There are also other supplemental stress patterns which should be considered when circumferential stress is concerned.
**Stress in the Axial Direction**

Axial stress is a normal stress pattern, parallel to the axis of cylindrical symmetry.

The stress in axial direction at a point in the tube or cylinder wall can be expressed as:

\[
\sigma_a = \frac{(p_i r_i^2 - p_o r_o^2)}{(r_o^2 - r_i^2)}
\]

where

\( \sigma_a \) = stress in axial direction (MPa, psi)

\( p_i \) = internal pressure in the tube or cylinder (MPa, psi)

\( p_o \) = external pressure in the tube or cylinder (MPa, psi)

\( r_i \) = internal radius of tube or cylinder (mm, in)

\( r_o \) = external radius of tube or cylinder (mm, in)

**Stress in the Circumferential Direction (Hoop Stress)**

The circumferential stress (hoop stress) is a normal stress in the tangential (azimuth) direction. Thin sections may have negligible small radial stress, but thicker-walled cylindrical shells require these stresses to be considered.

Lame’s theorem provides a solution to the thick cylinder problem. The theorem is based on the following assumptions

1. Material of cylinder is homogenous and isotropic

2. Plane sections of cylinder perpendicular to the longitudinal axis remain plane under the pressure
The stress in circumferential direction (hoop stress) at a point in the tube or cylinder wall can be expressed as:

\[
\sigma_c = \left[ \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} \right] - \left[ \frac{r_i^2 r_o^2 (p_o - p_i)}{(r_o^2 - r_i^2)} \right]
\]

where

\( \sigma_c = \text{stress in circumferential direction (MPa, psi)} \)

\( r = \text{radius to point in tube or cylinder wall (mm, in) \ ((r_i < r < r_o)} \)

maximum stress when \( r = r_i \) (inside pipe or cylinder)

(Engineering ToolBox, 2005).

Figure 1: Thick walled cylinder with open ends (Courses Washington).

Thick walled cylinders with open ends are loaded by internal pressure \( P_i \) and external pressure \( P_o \) as seen in figure 2. It also has an inner radius \( r_i \) and outer radius \( r_o \).
Both Hoop stress and longitudinal stress are produced within the wall when thick-walled tubes or cylinders are applied with internal and external pressures (Figure 2) (Courses Washington). Hoop stress is a significant component within engineering applications involving thick walled cylinders such as boilers, gun barrels, and high pressure containers, which are important factors in numerous industries such as power chemical, armament, and food processing industries (Prime 2011). Cylinders commonly succumb to cyclic stress during normal activity. Cracks can cause ruptures if large internal pressures produce high tension along the inner surface of the cylinders. Therefore, it is critical to analyze crack propagation in order to maintain the integrity of cylinders against stress failure (Salam et al., 2014).
Knowledge Gap

Based on Grossman's ideal root canal sealer properties, strengthening dentin and fracture resistance were not included. There is still a knowledge gap in terms of coming to a precise and definite method to test if sealers may improve dentin strength. An initial study applied hoop stress to test extracted human premolar teeth with no obturation material, gutta-percha with their respective sealers, and Tetranite® with no gutta-percha (Fossum et al., 2019). The previous study contained a limited sample size of the sole Tetranite® group and lack of information on the other sealer groups obturated without gutta-percha. It is still unknown if sole sealer groups of different materials may enhance dentin strength. Therefore, it is necessary to investigate how various sealers may affect dentinal strength and fracture without the use of gutta-percha.

II. Research Aim

Aim: To investigate the effects of hoop stress in roots that have been obturated by AH Plus sealer with no gutta-percha, EndoSequence Bioceramic sealer with no gutta-percha, and Tetranite® with no gutta-percha, on fracture and failure stresses.

Hypothesis

The null hypothesis is that fracture and failure stresses will show no significant differences among the sealer groups.
III. Materials and Methods

Extracted Teeth Collection

In order to test fracture loads, human extracted single-rooted premolars with fully formed apices were collected by the Division of Periodontology, Division of Oral and Maxillofacial Surgery, and the Division of General Dentistry at the University of Connecticut School of Dental Medicine. The Institutional Review Board (IRB) protocol was not required because samples were anonymous and were considered medical waste.

The exclusion criteria included teeth without fully formed apices, fractured roots, calcified root canals, internal or external root resorption, curvatures larger than 20 degrees, visible sealer voids at the surface of sectioned roots, and root canals with an oval shape after sectioning. Tooth root sections were only kept if the root canal system had a circular canals. The extracted premolars were stored in 0.5% Sodium Azide solution. The teeth were then randomly divided into groups based on sealers types. The groups were divided as followed:
Group 1: AH Plus Sealer with no gutta-percha (n= 15)
Group 2: EndoSequence Bioceramic Sealer with no gutta-percha (n= 16)
Group 3: Tetranite® with no gutta-percha (n= 14)

Teeth Cleaning, Shaping, and Irrigation

During preparation, the coronal portion of the premolars were removed at or below the cementoenamel junction (CEJ) with a low speed hand-piece and discs to the standardized root length of approximately 15 mm. Working length was first established using a #10 K-file within the canal until the tip was visualized at the apex. 1 mm was then subtracted from this apex to use for the final working length measurement.
Mechanical cleaning and shaping were done using the Protaper Gold rotary file system (Dentsply Maillefer, Ballaigues, Switzerland). The manufacturer's recommended rpm (revolutions per minute) and torque settings were used for each file. Each sample was then prepared using the same exact sequence of the Protaper Gold rotary files: SX, S1, S2, F1, F2, and F3 as the final apical size.

After each Protaper rotary file was used, the canals were irrigated by using 0.5% sodium hypochlorite (NaOCl). As the final irrigation step, 17% ethylenediaminetetraacetic acid (EDTA) was introduced into the root canals for 1 minute. The prepared teeth were then rinsed off with sterile distilled water to remove any residue of prior solutions. Before obturation, sterile paper points were used to dry root canals (Dentsply Maillefer, Ballaigues, Switzerland).

**Teeth Obturation**

Teeth in group 1 (AH Plus Sealer with no gutta-percha) were obturated using the lentulo spiral to introduce and pack the sealer into the root canal. To make sure the teeth were sealed as much as possible, at least 4 layers of the sealer were packed into the canal using the lentulo spiral so overflow from the coronal access of the teeth could be seen. After the teeth in group 1 were obturated, cavit was placed over the orifice and apex at a thickness of 2mm.

Teeth in group 2 (BC Sealer with no gutta-percha) were obturated in the same manner as in group 1. However, instead of AH Plus Sealer, BC Sealer was used to obturate the root canals. Similar to group 1, cavit was placed over the orifice and apex at a thickness of 2mm in group 2 teeth after obturation.

In group 3 (Tetranite® with no gutta-percha), teeth were obturated in the same manner as group 1 and group 2. After Tetranite® powder was mixed with distilled water in a liquid-to-powder ratio of 0.21 mL g⁻¹ for 20 s, the mixture was immediately obturated into the root canals with the lentulo spiral. Afterwards, cavit was placed over the orifice and apex at a thickness of 2mm in group 3 teeth.
After the obturation stage, teeth in all groups were placed into a solution of 0.5% Sodium Azide to allow the sealer/cement to set for a period of 7 days. All teeth were prepared and obturated by the single primary investigator.

**Stress Fracture Load Application**

Teeth from every group was then sectioned after removing the coronal portions, cleaning and shaping, irrigating, and obturating each to their respective sealer group. The teeth were sectioned serially into 2 mm thickness discs by using digital calipers, slow speed hand-piece, and slow speed diamond discs. As mentioned previously, tooth discs that had a symmetrical circular canal shape were kept for load application. Tooth discs that had asymmetrical or oval canal shapes were removed from groups. After sectioning the teeth, load was applied using the MTS 858 Mini Bionix® II Biomaterials Testing System (Figure 3). Four custom-made stainless steel pistons (.68 mm, .74 mm, .81 mm, .87 mm) were fabricated at the Institute of Materials Science at The University of Connecticut Storrs campus. One of the four stainless-steel pistons were selected to apply load on the sectioned teeth in conjunction with the testing system at a constant speed rate of 1mm/min directly on the sealer until fracture of the section occurred (Figure 4). The largest piston that would fit within the canal space, without touching the dentin wall was chosen for each sectioned tooth tested for load application.
TestWorks® 4 is the supplementary software system used in association with the MTS 858 Mini Bionix® II to show fracture forces in Newtons (Figure 5). Both software and the MTS 858 tabletop system will automatically stop loading application when fracture occurs. Photographs of fractured sectioned teeth were taken (Appendix II, Figure 9 - 11)

Figure 4: Various custom-made stainless steel pistons (.68 mm, .74 mm, .81 mm, .87 mm) applied to test load alongside the MTS 858 Mini Bionix® II at a constant rate of 1 mm/min directly on the sealer until fracture of the section occurred.
The stress generated by the sealer against the internal canal wall (Figure 6) was calculated by implementing the hoop stress formula for thick-walled cylinders (Figure 7), also known as Lame's Theorem. Mathcad® software was used to calculate hoop stress formulas for sectioned teeth discs (Appendix III, figure 12).

\[
\sigma_h = \frac{(p_i r_i^2 - p_0 r_0^2)}{r_0^2 - r_i^2} - \frac{(p_0 - p_i) r_0^2 r_i^2}{(r_0^2 - r_i^2) r^2}
\]

Figure 6: Hoop stress formula for thick-walled cylinders.
Figures are expressed as:

\[ \sigma_h = \text{hoop stress, i.e. stress in circumferential direction (MPa)} \]

\[ P_i = \text{internal pressure} \]

\[ P_o = \text{external pressure} \]

\[ r_i = \text{internal radius} \]

\[ r_o = \text{external radius} \]

\[ r = \text{radius at point of interest (usually } r_i) \]

**Statistical Analysis**

A one-way ANOVA analysis supplemented by the Tukey HSD 95% multiple comparisons range test was used to compare hoop stress failures for all sealer only groups (SPSS software).
IV. Results

The strength of dentin and amount of stress that was exerted by the different sealer groups on the internal dentin tooth wall during initial fracture is shown in Appendix I, Table 4. This raw data shows the separate sealer groups, distance from the center of canal to the outer dentin wall, distance from the center of canal to the inner dentin wall, force at time of fracture, piston size, and final calculated strength of dentin. The mean and standard deviation values for failure stress loads were $499.80 \pm 120.555$ MPa, $622.3125 \pm 83.7154$ MPa, and $708.2357 \pm 68.2772$ MPa for the AH Plus sealer with no gutta-percha group, BC sealer with no gutta-percha group, and Tetranite® group respectively.

The original sample size for each group included 17, 18, and 18 sectioned obturated discs for the AH Plus sealer without gutta-percha, BC sealer without gutta-percha and Tetranite® without gutta-percha groups respectively. However, a total of 8 sectioned discs were excluded from the results due to non-fractures. Ultimately, 15 samples were included for the AH Plus sealer group due to 2 non-fractured discs, 16 samples were included in the BC sealer group due to 2 non-fractured discs and 14 samples were included in the Tetranite® group due to 4 non-fractured discs.

A One-way ANOVA analysis was used to demonstrate that there was a statistically significant difference among the groups ($p < .0001$), which is shown in Table 1. Tukey's multiple comparison test showed that there were significant differences among all three groups. Multiple comparisons, illustrated in table 2, showed statistically significant differences between groups 1 (AH Plus sealer) and 2 (BC sealer) ($p < .002$), groups 1 and 3 (Tetranite®) ($p < .0001$), and groups 2 and 3 ($p < .042$). Table 3 and figure 8 represent the mean failure stress along with the standard deviations. As shown in both figures, the Tetranite® group expressed the highest mean failure stress with statistical significance. The AH Plus sealer group showed the lowest mean failure stress and the BC sealer group had the second highest mean failure stress value. All three groups displayed statistically significant differences.
Table 1: One-way ANOVA analysis.

<table>
<thead>
<tr>
<th>Stress</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>319545.018</td>
<td>2</td>
<td>159772.509</td>
<td>18.176</td>
<td>.000</td>
</tr>
<tr>
<td>Within Groups</td>
<td>369198.090</td>
<td>42</td>
<td>8790.431</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>688743.108</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Multiple Comparisons.

<table>
<thead>
<tr>
<th>(I) group</th>
<th>(J) group</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper Bound</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>-122.51250*</td>
<td>33.69615</td>
<td>.002</td>
<td>-204.3771</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-208.43571*</td>
<td>34.84131</td>
<td>.000</td>
<td>-293.0825</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>122.51250*</td>
<td>33.69615</td>
<td>.002</td>
<td>40.6479</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-85.92321*</td>
<td>34.31166</td>
<td>.042</td>
<td>-169.2832</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>208.43571*</td>
<td>34.84131</td>
<td>.000</td>
<td>123.7890</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>85.92321*</td>
<td>34.31166</td>
<td>.042</td>
<td>2.5633</td>
</tr>
</tbody>
</table>

* The mean difference is significant at the 0.05 level.

Group 1: AH Plus Sealer with no gutta-percha.

Group 2: BC Sealer with no gutta-percha.

Group 3: Tetranite® with no gutta-percha.
Table 3: Mean Failure Stress (Megapascal [MPa]).

<table>
<thead>
<tr>
<th>Stress</th>
<th>Subset for alpha = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>group</td>
<td>N</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Sig.</td>
<td></td>
</tr>
</tbody>
</table>

Means for groups in homogeneous subsets are displayed.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Figure 8: Failure stress (MPa) for each group.
V. Discussion

In vitro obturation studies may not directly correspond to clinical outcomes. However, these studies are justified for essential comparisons and screening of novel techniques, methods, and materials. Extracted human single canal premolars were effective test models that were easily handled and regulated.

Non-surgical endodontic treatment is first initiated with cleaning, shaping, and disinfection by supplementing hand or rotary files with various irrigation materials and techniques. Obturation then finishes the root canal procedure by attempting to fill the root canal system with a tight seal. With the use of modern and advanced rotary file systems, cleaning and shaping can be done more efficiently and with less errors compared to hand files (Hargreaves et al., 2011).

Nickel-titanium rotary instruments have been shown to be associated with inducing microcracks in dentinal root structure while being used (Saha et al., 2017). A large number of manufacturers have modified NiTi rotary systems such as the designs of cutting blades, body taper, tip configuration, and heat treatment. Although current rotary file systems have various advantages over hand filing, the rotary cutting blades me generate an increased amount of friction and stress within root canals (Blum et al., 2003). Despite its efficiency and requiring less time to shape and clean root canal systems, rotary files can also cause more instrument rotations within the canal (Pasqualini et al., 2008). Due to these rotational forces on the internal walls of root canals, many have speculated it may lead to microcracks and craze lines. Eventually, these craze lines may advance further and propagate into root fractures upon constant stress from endodontic and restorative procedures (Bier et al., 2009). Additional factors such as remaining dentin wall and amount of canal diameter after root canal preparation using various file tapers may influence stress distribution well (Rundquist et al., 2006).

The term “smear layer” was initially coined by McComb & Smith in 1975. These researchers suggested that smear layer created after instrumentation contained dentinal remnants, odontoblastic
process remnants, pulp tissue, and bacteria (McComb et al., 1975). Another description states that smear layer can be seen as “organic matter trapped within translocated inorganic dentine” (Lester et al., 1977). There has been controversy over whether the smear layer should be removed. Some investigators are in support of retaining the smear layer to block dentinal tubules and prevent bacterial exchange (Drake et al., 1994; Galvan et al., 1994; Pashley et al., 1981). Arguments in support for smear layer removal include its containment of bacteria, their by-products, and necrotic tissue (Goldberg & Abramovich 1977; McComb & Smith 1975; Wayman et al., 1979; Yamada et al., 1983). The smear layer may also act as a substrate for bacteria which allows deeper penetration into the dentinal tubules (George et al., 2005). Removing this component also improves the surface area by increasing the number of exposed dentinal tubules which results in sealers better adapting to the dentin (Sayin et al., 2007). Furthermore, smear layers can act as a barrier between filling materials and root canal wall which may compromise the formation of a satisfactory tight seal (Cergneux et al., 1987; Czonstkowsky et al., 1990; Foster et al., 1993; Lester et al., 1977; White et al., 1984; Yang & Bae 2002).

Numerous studies have shown the results of smear layer removal and its effects on respective sealer to dentin bond. One study demonstrated stronger AH Plus sealer to dentin bonding when the smear layer was removed (Eldeniz et al., 2005). Other sealers such as BC sealer express improved bonding quality when the smear layer is not removed due to the remaining moisture in the smear layer and its potential role as a coupling agent by facilitating the adaptation of hydrophilic materials to the root canal system (Lalh et al., 1999; Yildirim et al., 2008). Endosequence BC sealer is able to use the moist smear layer and produces a hydroxyapatite-like precipitation, which may chemically bond to dentin (Dawood et al., 2017).

Various irrigants and medications have been used in attempts to completely remove the smear layer. Irrigants should be able penetrate dentinal tubules for disinfection and offer long term
antimicrobial effects. Additionally, the cleaning stage should remove smear layer while being nontoxic and noncarcinogenic. The sole use of sodium hypochlorite may dissolve organic tissues but lacks the ability to remove inorganic components of the smear layer. Ethylenediaminetetraacetic acid (EDTA) is the most commonly used chelating agent to remove inorganic portions of the smear layer. EDTA is able to create a zone of demineralized collagen in dentin and dentinal tubules. These demineralized dentin zones promote dentin hybridization by allowing hydrophilic adhesives and sealers to infiltrate these areas. However, EDTA has been demonstrated little or no antibacterial effect in the root canal system (Torabinejad et al., 2003). The alternate use of EDTA and sodium hypochlorite has been recommended to remove the smeary layer as well as soft tissue and debris (Baumgartner & Mader 1987; Cengiz et al., 1990; White et al., 1984; Yamada et al., 1983). As stated before, this study used sequential irrigation of the root canal with 0.5% NaOCl, 17% aqueous EDTA, and finishing with EDTA for 1 minute to remove the smear layer. Distilled water was used as a final rinse to remove solution residue.

The main objective of sealers are to provide root canal obturations with a hermetic seal which should prevent leakage and ultimate reinfection of the root canal system. True hermetic seals help ensure will limit any leakage coronally, apically, or laterally. Despite differing opinions and controversy, one theory emphasizes the importance of sealer compared to the core material. Although gutta-percha may be considered as a component to “take up space”, sealers are the true components which provide entry into webs and fins which may provide the true key to a hermetic seal (Brave et al., 2007). Sealers could be of even more significance if these materials could offer enhanced dentin strength while promoting less fracture rates. There is currently a large knowledge gap in the field of endodontics for testing sealers and analyzing their potential to strengthen dentin. Further studies and analyses on dentin strength enhancement by sealers could improve obturation success rates and reduce fracture propagation in the future.

During this study, coronally removed premolars were obturated with either AH Plus Sealer with
no gutta-percha, EndoSequence Bioceramic Sealer with no gutta-percha, and Tetranite® with no gutta-percha. After obturation, the premolars were sectioned into 2 mm discs and acted as thick walled cylinders. By classifying these sections as thick walled cylinders, the hoop stress test was applied to these cylinders until fracture occurred. The fracture loads of sections of each sealer group were then compared to one another. Based on the results, the null hypothesis was rejected. There were significant differences in fracture loads amongst every group (Table 1 & 2). Tetranite®, the novel synthetic biomaterial, demonstrated to have the highest mean failure stress values with statistical significance. Endosequence BC Sealer with no gutta-percha had a lower mean failure stress compared to Tetranite®, but a higher mean failure stress when compared to AH Plus Sealer without gutta-percha; both with statistical significance. AH Plus Sealer had the lowest mean failure stress out of the three groups with statistical significance (Table 2 & Table 3).

The previous study entitled “Influence of Endodontic Sealers on Dentin Strength in Endodontically Treated Teeth”, focused on stress fracture load on extracted premolars which were mainly obturated with gutta-percha. The last experimental group tested used Tetranite® without gutta-percha and yielded a mean fracture stress of 879.3000 MPa which included 5 sectioned tooth samples and a relatively large standard deviation of 299.06 (Fossum et al., 2019). This group also had variable stress value range as low as 692.1 MPa and the highest value at 1405 MPa. In comparison, this current study showed a lower fracture stress value of 708.2357 MPa with a sample size of 14 sectioned discs and a smaller standard deviation value of 68.2772 MPa for the Tetranite® group. The lowest stress value was 570.4 MPa while the largest value was 749.4 MPa. With a larger sample size, smaller standard deviation supplemented by a smaller range of value, this current study may express a more accurate representation of failure stress load for teeth obturated by this novel bone adhesive material. Additionally, the previous study concentrated hoop stress test on teeth obturated with both sealer and gutta-percha. The experimental group from the previous study also concentrated on teeth obturated...
with both core gutta-percha material with respective sealers. Failure stress load values were 288.0889 MPa, 300.1750 MPa, and 351.0286 MPa for AH Plus Sealer and gutta-percha, BC Sealer and gutta-percha, and Tetranite® with gutta-percha respectively. In comparison, the current study focused on sealers with no gutta-percha. The mean failure stress values were 499.80 MPa, 622.3125 MPa, and 708.2357 MPa for AH Plus Sealer with no gutta-percha, BC Sealer with no gutta-percha, and Tetranite® with no gutta-percha respectively. Based on these results, the respective experimental groups from both studies were quite different, with lower failure stress loads for the groups using gutta-percha. This lower stress values may be due to the core material exerting a substantially larger amount of force and pressure onto the dentin wall. Due to these differences in failure stress values, it was necessary for this study to continue the previous study's experimentation, and test sole sealer groups without the use of core gutta-percha.

A total of 8 sectioned obturated discs were excluded from the study because stress fracture loads administered by the MTS 858 Mini Bionix® II Biomaterials Testing System with respective piston sizes did not elicit disc fractures. 2 sectioned discs, 2 sectioned discs, and 4 sectioned discs did not fracture for the AH Plus sealer with no gutta-percha group, BC sealer with no gutta-percha group, and Tetranite® with no gutta-percha group respectively. One possible explanation for non-fractured samples could be due to a lack of core material. Without a more resistant core material such as gutta-percha, pistons may penetrate void-filled or improperly obturated sole sealer material upon stress load. An alternate view on non-fractured sectioned discs may be explained by set sealer material being able to withstand stress load forces without fractures occurring.

According to the Bloodborne Pathogens Standard of the Occupational Safety and Health Administration (OSHA), extracted human teeth used for research may be a potential source for bloodborne pathogens (Recommended infection-control practices for dentistry, 1993). For this reason, sterilization and storage during their use is paramount. In addition to eliminating bacteria, storage
media should be able to keep the extracted teeth moist. Myriad methods of storage such as distilled water, sodium chloride, sodium hypochlorite, chloramine, formalin, and glutaraldehyde have been tested for effective storage mediums and sterilization (Lee et al., 2007). Other techniques for storage include changing temperatures such as refrigerating and freezing samples (Zheng et al., 2005; Secilmis et al., 2011). In general, no significant differences were seen in bond strength to the enamel of teeth stored in wet media for 5 years (Williams et al., 1985) or sterilized specimen (Shaffer et al., 1985).

Although the aforementioned storage mediums exist, many come with negative effects to the extracted teeth. Sodium hypochlorite was not chosen as a viable storage source due to significantly lowering bond strength of specimens (Lee et al., 2007). Chloramine is another storage product that has been used and is related to sodium hypochlorite. However, similar to its close relative, chloramine, as well as physiological saline, has shown to cause significantly lower bond strengths in teeth (Retief et al., 1989). Sterilization with autoclave was shown to negatively affect bond strengths of teeth stored initially in distilled water or 10% formalin as well (Lee et al., 2007).

As previously stated, maintaining dentinal moisture content will affect the structural integrity of the tooth as well as outcome of sealing dentin-material interface (Al Qahtani MQ et al., 2003; Gallo JR et al., 2000; Miears JR et al., 1995; Pashley DH et al., 1997). Moisture in dentin is also important to maintain the integrity of intertubular collagen networks and dentinal tubules (Carvalho RM et al., 1996; Van Meerbeek B; 1993). However, an over excessive and high moisture content of dentin or residual liquids within the root canal showed to prevent sealing within the dentin-material interface. Oppositely, over desiccation on the root canal system could collapse the demineralized dentin and negatively influence resin-based sealer infiltration.

In this study, extracted teeth were stored in 0.5% Sodium Azide solution. Sodium Azide is a commonly used storage medium for laboratory reagents that contains qualities which inhibit microbial growth in teeth. This solution is able to deter microbial growth by implementing a mechanism which
involves metal ion complexation and displacement from enzymes (Komabayashi et al., 2009).

Additionally, cross-linking of collagen is not expected because Sodium Azide is not a fixative. Sodium Azide is able to increase dentin moisture for 1 day but does not further increase moisture past 24 hours (Komabayashi et al., 2009).

A limitation of this study may originate from the lack of sample sizes for each test group. Although there were at least 14 useable sample sizes for each group, future studies may attempt to collect a larger sample size for more accurate mean failure stress values. Another limitation of this study was not dividing tooth sections into coronal, middle, and apical thirds. Instead, the sectioned discs with the most uniformly circular shaped canals were chosen for each group. Different locations of the root may express different values. For example, dentin I the apical third contains a smaller amount of dentinal tubules and reduced diameters. This will cause a smaller area for sealer to disperse into compared to the middle or coronal thirds. In addition to having more complex tubular structures, the coronal portion of the root canal also has a higher number of dentinal tubules. Along with a larger amount of dentinal tubules, coronal thirds have larger diameters of dentinal tubules which allows sealer to penetrate these areas much better compared to the middle or apical thirds (Carneiro et al., 2012; Nagas et al., 2011). These variations along the root canal may explain the larger standard deviation values.

**Future Studies**

Expanding experimental groups to different types of sealers and core materials may improve our understanding of various obturation techniques and their respective fracture loads on teeth. Although Tetranite® has not been introduced into the dental market as an endodontic sealer, modifications may be made to improve its flow rate, working time, biocompatibility, and dentinal bonding. With future studies, this novel bone adhesive may become a commonly used sealing agent. In addition, tooth selection and tracking location of sections may be modified to improve this study. For
example, multirooted and teeth with multiple canals may influence fracture load results. Also, distinguishing sectioned discs to specific locations such as the coronal, middle, or apical third may effect future fracture load studies. Finally, having a more robust sample size with various obturation techniques may give us a better understanding of sealers and their effect on fracture load of teeth.

VI. Conclusion

Implementing the hoop stress test introduces a novel method of testing sealers and their influence on dentin strength. In the field of endodontics, there is a current knowledge gap on methods applied to test if sealers potentially enhance dentin strength of the root canal. With the use of hoop stress on sectioned teeth as thick cylindrical test models, we are able to demonstrate different sealers' capabilities of improving dentin strength and fracture loads of root canal systems. This study revealed that Tetranite® significantly increased fracture stress compared to AH Plus sealer and Endosequence BC sealer. BC sealer also significantly improved fracture load on extracted teeth compared to the AH Plus sealer group. Within the limitations of this study, Tetranite® improved dentin strength of extracted teeth and may be considered as a potential sealer with further studies and improvement of the material as an actual obturation material.
## VII. Appendix

### Appendix I: Raw data

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<th>R0 (distance from center of sealer to outer wall)</th>
<th>R1 (distance from center of sealer to inner wall)</th>
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Table 4: Raw Data Collection.
Appendix II: Examples of Fractured Sectioned Obturated Discs

Figure 9: Example of fractured obturated disc.

Figure 10: Moment of disc fracture.

Figure 11: Fractured disc.
Appendix III: Software for Hoop Stress Test of Thick-Walled Cylinder

Figure 12: Mathcad® Copyright 1987-2018 © PTC Inc., 140 Kendrick Street, Needham, MA 02494 U.S.A. All rights reserved.
Appendix IV: Workstation during tooth preparation, obturation, sectioning, and storage

Figure 13: Workstation setup for preparing extracted teeth using (surgical operating microscope M320, Leica Microsystems).
VIII. References


Courses Washington, University of Washington. Thick Walled Cylinders. courses.washington.edu/me354a/Thick%20Walled%20Cylinders.pdf.


