AN IN VITRO ASSESSMENT OF THE SETTING EXPANSION OF GRAY AND WHITE MINERAL TRIOXIDE AGGREGATE

A THESIS
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DEDICATION

To my siblings and family in-law, for tolerating my inflexible schedule over the past many years, and supporting both of us through it all...

To my parents, for your guidance and support throughout my life, as well as the example you’ve always set of a loving and successful relationship...

To Betsy, we’ve been through a great many adventures in our time together, and without your support I know I wouldn’t be the man I am today...

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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .................................................. i
DEDICATION ................................................................ ii
TABLE OF CONTENTS .................................................. iii
LIST OF FIGURES ........................................................ iv
LIST OF TABLES .......................................................... v
INTRODUCTION ............................................................. 1
REVIEW OF THE LITERATURE .......................................... 2
  MINERAL TRIOXIDE AGGREGATE ....................................... 2
  WHITE PROROOT MTA ................................................ 3
  SETTING TIME .......................................................... 4
  LEAKAGE ................................................................ 4
  MARGINAL ADAPTATION ............................................. 7
  BIOCOMPATIBILITY .................................................... 7
  ADDITIVE TO ALTER WORKING PROPERTIES .................. 10
  SETTING EXPANSION ................................................ 11
HYPOTHESIS AND SPECIFIC AIMS ................................. 15
MATERIALS AND METHODS ........................................... 16
  RESEARCH DESIGN .................................................. 16
  STATISTICAL ANALYSIS ............................................ 20
RESULTS ................................................................... 21
DISCUSSION ............................................................... 25
CONCLUSIONS ............................................................ 29
REFERENCES ............................................................... 30
APPENDIX I ................................................................. 37
ADDENDUM ................................................................. 38
<table>
<thead>
<tr>
<th>FIGURE #</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Decoloration of methylene blue dye</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>PDL cells spreading to demonstrate biocompatibility</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Linear setting expansion of MTA cements</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Optical triangulation</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Contour map of control sample #1</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Contour map of GMTA sample #5</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>Setting expansion measured by the 3D method</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Setting expansion measured by the slice method</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Setting expansion of GMTA sample 3</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>GMTA setting expansion comparing methods</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Surface scans of WMTA sample 5</td>
<td>27</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE #</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Descriptive Statistics for 3D Method</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Descriptive Statistics for Slice Method</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Linear expansion of gray and white MTA samples</td>
<td>40</td>
</tr>
</tbody>
</table>
INTRODUCTION

Mineral trioxide aggregate (MTA) was developed at Loma Linda University in an effort to create an “ideal” root end filling and perforation repair material. The combination of properties found to be lacking in existing materials were sealing ability, marginal adaptation, biocompatibility, and handling properties (Gartner, Dorn, 1992). According to multiple studies, MTA outperforms the traditionally available materials in each of these categories (Torabinejad et al., 1993; Nakata et al., 1998).

The impact of MTA on both the practice of endodontics and the literature base has been great. PubMed searches for mineral trioxide aggregate, ProRoot (Tulsa Dentsply’s commercially available form of MTA), and Portland cement (which has comparable components to and is often compared with MTA) yielded 1304 articles. Although it has been extensively studied, relatively few studies exist regarding the setting expansion of MTA. As the clinical applications of MTA expand to include root canal obturation, information on its physical properties may help avoid potential vertical root fractures and other untoward events.
REVIEW OF THE LITERATURE

The objectives of endodontic therapy are the elimination of pulp tissue, bacteria, and bacterial byproducts while creating a tapered preparation that is confined to the root canal space (Schilder, 1974). Root perforation is a complication of root canal therapy that occurs when a misdirected instrument penetrates into the surrounding periodontal tissues (Wong, Cho, 1997). Endodontic procedures account for 47 percent of iatrogenic perforations, and these most often occur when searching for canal orifices, negotiating calcified canals, or during canal instrumentation (Kvinnsland et al., 1989).

The main complication of perforation is the potential for inflammatory periodontal involvement and loss of attachment, eventually causing tooth loss (Wong, Cho, 1997). An ideal perforation repair material seals the defect and adheres to tooth structure, as well as exhibits insolubility, dimensional stability, radiopacity, and biocompatibility. The materials historically utilized for perforation repair include amalgam, zinc-oxide-eugenol materials, composite resins, and glass-ionomer cements (Johnson, 1999). Amalgam had been demonstrated to create the most favorable environment for healing (ElDeeb et al., 1982), however healing occurs in only 54 to 56 percent of cases (Benenati et al., 1986; Kvinnsland et al., 1989).

**Mineral Trioxide Aggregate**

MTA was introduced as a perforation repair and root end filling material in 1993 (Lee et al., 1993; Torabinejad et al., 1993). MTA is basically composed of Portland cement—lime, silica, alumina, and iron oxide (Dammaschke et al., 2005). The original components of MTA were reported to be tricalcium silicate, tricalcium aluminate,
tricalcium oxide, silicate oxide, and other mineral oxides (Torabinejad et al., 1993). The composition of gray MTA (GMTA) listed on the material safety data sheet from Tulsa Dentsply, the manufacturer of the commercially available ProRoot MTA, consists of tricalcium silicate, bismuth oxide, dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite, and calcium sulfate dehydrate or gypsum (Tulsa Dentsply MSDS).

**White ProRoot MTA**

A white form of ProRoot MTA (WMTA) became available in 2002 in order to address esthetic concerns caused by perforation repairs in esthetic areas. Varying results have been reported; however, it is generally accepted that the difference in formulation is a reduction of tetracalcium aluminoferrite (Asgary et al., 2005; Al-Hezaimi et al., 2005; Matt et al., 2004). The discoloration caused by GMTA has been successfully demonstrated to be reversible in case reports of replacement by WMTA (Bortoluzzi et al., 2007).

Utilizing electron probe microanalysis, the new WMTA differs from the previous GMTA by a decrease of 55% of the aluminum oxide, 56.5% of the magnesium oxide, and 90.8% of the iron oxide (Asgary et al., 2005). X-ray spectroscopy and analysis demonstrated differences between the elemental analysis of WMTA and its patented formulation. The analysis demonstrated no iron present in comparison to the 2.8% by weight in the patent (Dammaschke et al., 2005).

Particle size has been noted as a major difference between MTA and the Portland cement from which it was derived (Islam et al., 2006). WMTA particle size was modified by the manufacturer to improve the handling properties in 2003. WMTA may represent
an improvement in this regard, as its average particle size is smaller than GMTA (Duarte et al., 2003). The aforementioned differences notwithstanding, GMTA and WMTA produce similar results (Parirokh et al., 2005; Hamad et al., 2006)

**Setting time**

Mixed together with the sterile water supplied, (3:1 powder:water) the hydrophilic MTA powder creates a colloidal gel that solidifies after 3-4 hours (Torabinejad et al., 1995b). In a comparison study, Torabinejad et al. reported setting times for the repair materials amalgam, Super-EBA, IRM, and MTA were 4, 9, 6, and 165 minutes, respectively. The gypsum content of MTA, roughly half the percent by weight of Portland cement compounds, is largely responsible for its setting time (Dammaschke et al., 2005). According to the developers of MTA, the setting time provides reduced shrinkage and better marginal seal (Torabinejad et al., 1995b, 1993).

In a 2006 study, Kogan et al. found that the setting time of MTA can range from 20 minutes to 120 minutes depending on the liquid used for hydration (Kogan et al., 2006). The set time was 50 minutes using the sterile water provided, which Kogan attributed to changes in the composition of MTA since its release. Asgary et al. demonstrated a compositional change, specifically decreased phosphate presence, since Torabinejad’s original research data was published in 1993 (Asgary et al., 2005).

**Leakage**

Bacteria are the cause of pulpal and periradicular disease (Kakehashi et al., 1965; Möller et al., 1981; Lin et al., 2006). A tight seal between dental restorative materials and tooth structure is critical to the elimination of irritation to vital tissues and endodontic
disease (Bergenholtz et al., 1982; Sabeti et al., 2006). Leakage of MTA has been studied using dyes, fluid filtration, and bacterial penetration.

Methylene blue or Rhodamine B fluorescent dye penetration was evaluated microscopically, and MTA exhibited significantly less leakage than amalgam, IRM, or super EBA (Lee et al., 1993; Torabinejad et al., 1993). The decoloration of methylene blue dye when in contact with restorative materials brings the validity of certain findings into question (Wu et al., 1998a). Figure 1 demonstrates the decrease in optical density of methylene blue when exposed to GMTA, ZnOE, and other materials used in endodontics. Contact with GMTA decreased optical density by 84% over the first 24 hours of the study. When distance of dye penetration is used as a model for microleakage, the inability to detect decolored dye may be inappropriately interpreted as a lack of dye penetration.

Fluid filtration models test the ability of a material to maintain a seal against pressure by measuring fluid movement in a closed system. GMTA provided a superior
seal when compared to amalgam in numerous fluid filtration models (Bates et al., 1996; Wu et al., 1998b; Fogel, Peikoff, 2001). GMTA demonstrated non-significant differences with IRM and super-EBA (Bates et al., 1996; Fogel, Peikoff, 2001), as well as demonstrating a decrease in leakage over time rather than the increase found with super-EBA (Wu et al., 1998b).

Because the etiology of pulpal and apical disease is bacteria, leakage models evaluating bacterial ingress may be the most clinically relevant (Adamo et al., 1999). Torabinejad et al. found GMTA allowed no \textit{S. epidermidis} penetration at 90 days when placed as a root end filling, which was significantly less than amalgam, IRM, and super-EBA (Torabinejad et al., 1995d). Nakata et al. challenged the seal of GMTA and amalgam as perforation repair materials with \textit{F. nucleatum}. Amalgam perforation repairs leaked significantly more than GMTA, which demonstrated no leakage throughout the 45 day testing period (Nakata et al., 1998). GMTA, WMTA, and resin-modified glass ionomer coronal barriers challenged by human salivary bacteria demonstrated minimal leakage at 90 days, resulting in the recommendation of each material for this purpose (Tselnik et al., 2004).

Endotoxins are small components of the membrane of Gram-negative bacteria composed of a Lipid A moiety and a polysaccharide tail (Rietschel, Brade, 1992). When released from the membrane upon lysis, the endotoxins stimulate inflammatory pathways through the release of mediators from macrophages, resulting in fever, clotting, hypotension, and shock (Rietschel et al., 1994). Studies have correlated the presence and concentration of endotoxin with inflammation of the apical tissues (Schein, Schilder,
As components of the bacterial membrane are much smaller than whole bacteria, the penetration of endotoxin was studied by Tang et al. in an extracted tooth root end filling model. GMTA demonstrated significantly less endotoxin penetration than amalgam, IRM, and super-EBA (Tang et al., 2002).

**Marginal Adaptation**

Marginal adaptation of GMTA has been previously studied under scanning electron microscope with varying results. Torabinejad et al. found GMTA’s marginal adaptation to be superior to amalgam, IRM, and super-EBA (Torabinejad et al., 1995e). Superior adaptation was also demonstrated with GMTA over IRM and super-EBA following various finishing techniques (Gondim et al., 2003). Following the application of occlusal forces in a computer controlled apparatus, GMTA marginal adaptation was reported to be significantly better than a ZOE preparation (Peters, Peters, 2002).

Marginal adaptation has been related to the sealing ability of restorative materials (Stabholz et al., 1985): however, evaluating both dye leakage and marginal adaptation, Xavier et al. demonstrated no correlation between the two methodologies. Silver nitrate penetration was greater with an MTA cement (MTA Angelus) than super-EBA, while marginal adaptation was superior for the MTA cement under scanning electron microscope (Xavier et al., 2005).

**Biocompatibility**

The biocompatibility of restorative material in contact with the apical tissues is an important factor (Kettering, Torabinejad, 1995; Keiser et al., 2000; Torabinejad et al., 1995c). Torabinejad et al. utilized multiple *in vitro* methods with mouse periodontal
ligament (PDL) fibroblasts to demonstrate the cytotoxicity of the root end filling materials IRM, super-EBA, amalgam, and GMTA. The results indicated significantly lower cytotoxicity from GMTA when compared with IRM or super-EBA (Torabinejad et al., 1995c). Similar results were demonstrated in research performed with human PDL fibroblasts, GMTA demonstrating lower cytotoxicity compared with amalgam or super-EBA (Keiser et al., 2000).

Zhu et al. introduced human osteoblasts to set GMTA and observed adhesion and spreading of the cells to form a monolayer, indicating a favorable response (Zhu et al., 2000). Using scanning electron microscopy, Balto concluded that the quality and quantity of cell attachment to a retrofilling material could be used as a criterion to evaluate the material's toxicity. Comparison of fibroblast attachment to set GMTA and freshly mixed GMTA demonstrated increased attachment and spreading in the set group, indicating lower toxicity with GMTA after 24 hours (Balto, 2004). Fayad et al. observed similar attachment of PDL cells to MTA and resected root surface, but no attachment on gutta percha (Fayad et al., 2004).

Figure 2. Human PDL cells (A) are shown spreading similarly on a resected root surface (B, left image) and on GMTA (B, right image) (Fayad et al., 2004)
Prevention of periodontal tissue inflammation and attachment loss are the goals of perforation repair (Kettering, Torabinejad, 1995; Keiser et al., 2000; Torabinejad et al., 1995c). The ability to induce hard tissue formation is a favorable property for a perforation repair or root end filling material. Cementogenesis requires the regulated action of cementoblasts and osteoblasts, and potentially fibroblasts (Saygin et al., 2000). In an *in vitro* study involving fibroblasts from the PDL and gingiva, WMTA was demonstrated to induce expression of alkaline phosphatase activity. This expression is indicative of osseous repair and cementum deposition (Bonson et al., 2004).

Torabinejad et al. noted cementum deposition associated with GMTA when applied as a root end filling material in an *in vivo* canine model (Torabinejad et al., 1995a). Other studies utilizing canine models demonstrated similar results: GMTA was the only material found to induce cementum formation (Economides et al., 2003; Baek et al., 2005). The findings of Bonson et al. may explain the aforementioned cementum repair associated with GMTA.

Deposition of bone adjacent to GMTA implanted in the mandibles of guinea pigs further demonstrates its biocompatibility and repair potential (Saidon et al., 2003). Sarkar et al. reported white precipitates on the surface of GMTA utilizing scanning electron microscopic analysis and X-ray diffraction. The authors concluded that calcium ions released from mineral trioxide aggregate react with phosphates in tissue fluid to yield hydroxyapatite, which leads to bone formation (Sarkar et al., 2005). The involvement of the calcium ions and similarity between crystals observed on the surface of GMTA and
WMTA with hydroxyapatite has been reinforced by another study utilizing the same techniques (Bozeman et al., 2006).

**Additives to Alter Working Properties**

Delayed placement of a permanent restoration is a factor that has been demonstrated to decrease the incidence of healing (Keiser et al., 2000). Decreasing the setting time of MTA could provide benefits such as the ability to place an immediate restoration or the ability to more thoroughly irrigate the crypt during surgery. MTA’s setting reaction is a hydration reaction (Gancedocaravia, Garciaabarero, 2006), therefore sufficient water must be present and available in any substitute for the sterile water provided.

In the clinical setting, saline and local anesthetics are often mixed with MTA rather than the supplied sterile water due to availability, defect size variation, and desire to conserve materials. MTA cements mixed with sterile water, lidocaine, and saline performed similarly in one study (Vanderweele et al., 2006), while 2% lidocaine and saline increased both setting time and compressive strength in another (Kogan et al., 2006). When clinicians consider the utilization of different liquids to prepare MTA, potential alterations of physical and biological properties should be of greater concern than convenience (Kogan et al., 2006).

Chlorhexidine is popular in endodontics because it provides antimicrobial activity and substantivity, while not affecting the set of common root canal sealers (Jeansonne, White, 1994; White et al., 1997; Ferguson et al., 2003). The substitution of .12% chlorhexidine gluconate decreased the setting time and led to an increase in antimicrobial
activity, but the resulting MTA was crumbly and difficult to place (Stowe et al., 2004). Hernandez et al. found the chlorhexidine substitution altered the biocompatibility of MTA as well, inducing apoptosis of mouse gingival fibroblasts (Hernandez et al., 2005). Preparation of MTA with a chlorhexidine gel formulation resulted in a mixture that did not set, but NaOCl gel formulation improved working properties (Kogan et al., 2006). These studies demonstrate that chlorhexidine is not suitable as an additive to MTA cements.

Other additives to the liquid, such as calcium chloride, have been shown to decrease the set time without negatively affecting the physical or biological properties of the resulting repair material (Bortoluzzi et al., 2006, 2009; Wiltbank et al., 2007). Calcium chloride increases the rate of hydration of Portland cements, thereby accelerating the setting reaction (Kosmatka et al., 2002). A mixture of 2% calcium chloride with 1% methylcellulose decreased the setting time while providing handling characteristics similar to IRM, the subjective control (Ber et al., 2007). These benefits notwithstanding, MTA is still manufactured for use with the provided sterile saline and no additives.

**Setting expansion**

Although both the relevance and statistical flaws of leakage models have been questioned for decades (Wu, Wesselink, 1993; Schuurs et al., 1993), their continued presence in the literature commands attention. Matt et al. demonstrated a statistically significant difference in leakage between the gray and white formulations of MTA as root end filling materials when challenged by methylene blue dye (Matt et al., 2004).
Similarly, Chng et al. found GMTA resisted methylene blue dye leakage significantly more than WMTA (Chng et al., 2005). Studies that demonstrated statistically insignificant differences include penetration challenges with *F. nucleatum*, unspecified salivary microbes, or India ink dye (Ferris, Baumgartner, 2004; Tselnik et al., 2004; Hamad et al., 2006).

The expansion of MTA cements upon setting may be responsible for decreased leakage and enhanced marginal adaptation (Storm et al., 2008). Excessive expansion is undesirable when MTA material is employed as a root-end filling material as it may lead to cracks in the root (Islam et al., 2006). Differences in setting expansion between GMTA and WMTA may, according to Storm et al., explain varying results in the aforementioned leakage studies. This proposed correlation invites further investigation into the setting expansion of MTA cements.

The International Organization for Standardization (ISO) and the American National Standards Institute (ANSI) are the oversight organizations governing material standards and conformity issues in dentistry, as well as many other fields. ISO 6786:2001 is the standard that governs dental root canal sealing materials, and it provides a testing methodology for the assessment of conformity. In accordance with ISO 6786:2001, Islam et al. and Chng et al. demonstrated a mean expansion of .30% for WMTA and .28% for GMTA—a non-significant difference (Islam et al., 2006; Chng et al., 2005).

MTA cements and other materials used as root end filling materials are explicitly excluded from the scope of the ISO technical standards for root canal filling materials (Hauman, Love, 2003). Further, the ISO 6786:2001 protocol for dimensional change is
designed to assess measurable changes after the material is set, and for the subsequent thirty days. Ørstavik et al., when researching the proposed protocol for the standards, noted the accuracy of the test methodology may not sufficiently detect dimensional changes suggested as a maximum limit for expansion (Ørstavik et al., 2001).

Storm et al. developed a linear expansion measuring device in order to assess the true hygroscopic linear setting expansion of MTA cements (Storm et al., 2008). MTA samples (.6 grams total mass) were prepared and compacted into a cylindrical mold that was constrained at one end. The other end of the cylinder was covered with sterile saline or Hank’s balanced salt solution, and a nylon piston attached to a linear variable displacement transformer recorded the position change each second for a 24 hour period.

The results, illustrated graphically in Figure 3 below, demonstrated significantly more setting expansion in GMTA than WMTA regardless of the setting medium. Another notable finding was that 50% of the setting expansion seen at 24 hours was achieved in the first 5 hours (300 minutes). The ability to record expansion every second for 24 hours reveals a clear picture of the rate of MTA’s linear expansion.

![Figure 3: (A) kinetics of linear expansion of gray MTA, Portland Cement, and white MTA. (B) Mean linear setting expansion](image-url)
As no standard has yet to be applied to the measurement of the setting expansion or dimensional stability of MTA cements, an *in vitro* method was developed to study MTA cements that more closely simulates the clinical setting. The purpose of this study was to compare the volumetric change in MTA during setting in an extracted tooth model.
HYPOTHESIS AND SPECIFIC AIMS

The hypothesis being tested is that there is a difference between the setting expansion of the gray and white formulations of MTA. The null hypothesis is that no difference in setting expansion exists between GMTA and WMTA. The specific aims of this study are to demonstrate the setting expansion of MTA cements using an in vitro study design and equipment capable of measuring the volumetric expansion for a given area.
MATERIALS AND METHODS

The research protocol used in study was exempted from approval by the Institutional Review Board of the University of Minnesota. Thirty-eight extracted, single rooted premolar teeth were collected from the Oral Surgery and Periodontology clinics at the University of Minnesota School of Dentistry, Hennepin County Medical Center, and the VA Hospital in Minneapolis. The teeth were examined for cracks or fractures with 3.5x magnification dental loupes (Orascoptic. Middleton, WI) and trans-illumination. Each tooth was mounted in dental stone with the coronal tooth structure and lateral aspect of the root exposed, which was necessary for the scanning process.

The teeth were randomly divided into 2 groups of 18 teeth and a control group with two teeth. Group 1 received gray MTA perforation repair, group 2 received white MTA perforation repair, and the control teeth received no repair of the perforation. The perforation repairs were carried out with equal numbers of each group in multiple sessions in order to acquire the preliminary scan shortly after hydrating the MTA. Endodontic access to the pulp chamber was made through the crown of each tooth followed by complete removal of the chamber roof. Tissue remnants were removed with 3 ml 5.25% NaOCl irrigation. Lateral perforation was performed with a #2 round bur 2 mm apical to the CEJ of each tooth, followed by irrigation with 5.25% NaOCl. The tooth was positioned against a matrix to simulate periodontal tissues during placement of the repair material.

MTA was mixed with 2% lidocaine (powder:liquid mass ratio of 3:1) on a glass slab with a stainless steel spatula. MTA was placed into the perforation initially with an
Endo Gun (Medidenta Intl, Inc. Woodside, NY) and compacted with Perf Paddle #1 (CK Dental Industries. Orange, CA). A moist cotton pellet was placed into the chamber, followed by provisional restoration of the access with Cavit temporary filling material (3M ESPE. St. Paul, MN). Care was taken to ensure the surface of the MTA was not disturbed by contact in any way from this point forward.

Samples were evenly spray-coated with Magnaflux Spotcheck SKD-S2 Developer (Magnaflux Global Solutions. Glenview, IL) under a laboratory hood prior to both the 0 and 24 hour scans. The spray consists of a blend of inert inorganic particles suspended in a solvent blend including isopropyl alcohol and acetone. Preliminary samples demonstrated the necessity of this step in order to create a non-transparent, diffuse surface compatible with the scanning device. The pilot studies also showed the spray coating did not affect the results of the scanning process.

A three dimensional scanning device, the Lava Scan ST scanner (3M ESPE. St. Paul, MN), was utilized to capture the surface of each sample at two time points, referred to as 0 hour and 24 hour scans. The Lava Scan ST scanner is a non-contact, white light optical 3D-scanning device. The operating principle is based on phase contrast combined with triangulation methods. A fringe pattern is projected onto the model’s surface and imaged by a video camera under a certain angle. Seven separate images are acquired from different perspectives and superimposed in order to get the entire 3D data. Point resolution of the system is 0.060 mm with a point accuracy of 0.005 mm.
Following the initial scan the samples were stored in Hank’s balanced salt solution and allowed to set for 24 hours. Spotcheck was reapplied to the samples and they were again submitted to the LavaScan ST optical scanner. The images were extracted from the LavaScan machine and analyzed with Cumulus image analysis software (alpha build, University of Minnesota).

Cumulus allows the comparison of LavaScan produced images by aligning the images, evaluating surface changes with contour maps, selecting regions of interest, and quantifying the change (Figures 5 & 6). Images are aligned using multiple surface points or regions, with the parameters of the fit controlled by the operator. Contour regions were set to 250 microns to evaluate even minimal expansion. The regions of interest were outlined on the 0 and 24 hour scans and compared for volume change using two analytical methods, a triangle and a slice method.
Figure 5. The contour map of control sample #1 demonstrating minor changes on the tooth surface and no change in the unrepaired perforation (arrow). Regions that appear black are either beyond the range of the scale, or could not be scanned.

Figure 6. Contour map demonstrating the surface changes of GMTA sample 5. The white arrow indicates the region of the perforation repair material, which expanded between 50 μm and 100 μm. The black arrow indicates an area beyond the region of the scale of expansion, or an area that could not be scanned.
The data collected was volume change by triangle method (Vol3D), volume change by slice method (VolSlice), surface area by triangle method (SA3D), and surface area by slice (SASlice). From these data, the volume change per unit area was calculated with each method (VperSA3D, VperSASlice).

**Statistical Analysis**

Descriptive statistics (mean, standard deviation, and range) were calculated for measures collected from the slice and 3D methods for the GMTA and WMTA groups. Mean volume change/unit area was compared between GMTA and WMTA using a two-group t-test. One-sample t-tests were also conducted to see if GMTA and WMTA had mean volume changes per unit area significantly greater than zero. P-values less than 0.05 were considered statistically significant. SAS v9.1.3 was used for the analyses.
RESULTS

The mean volume change per unit area for the 3D method of WMTA was not different than the mean volume change per unit area of GMTA (Table 1). The mean volume change per unit area of both the WMTA and GMTA were statistically significantly greater than zero ($p < 0.0001$ and $p < 0.0001$, respectively). These results indicate an increase in volume per unit area from 0 hours to 24 hours. WMTA sample #12 produced an aberrant result when analyzed with the 3D method, but a sensitivity analysis revealed its inclusion did not alter the results.

<table>
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<th>Statistic</th>
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<th>WMTA n=18</th>
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<td>Mean (SD)</td>
<td>Range</td>
</tr>
<tr>
<td></td>
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<td>0.030-0.776</td>
</tr>
<tr>
<td><strong>Unit Area (UA)</strong></td>
<td>Mean (SD)</td>
<td>Range</td>
</tr>
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<td></td>
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<td>1.199-5.562</td>
</tr>
<tr>
<td><strong>Volume per UA†</strong></td>
<td>Mean (SD)</td>
<td>Range</td>
</tr>
<tr>
<td></td>
<td>0.046 (0.031)</td>
<td>0.010-0.139</td>
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|† t-test p-value = 0.889

Figure 7. Setting expansion measured by the 3D method. Each bar represents one sample, which are arranged in ascending order for trend visualization.
For the Slice method, the mean volume change per unit area of WMTA was not different than the mean volume change per unit area of GMTA (Table 2). Once again, the mean volume change per unit area of WMTA and GMTA were statistically significantly greater than zero (p < 0.0001 and p < 0.0001, respectively), indicating an expansion upon setting.

Table 2. Descriptive Statistics for Slice Method

<table>
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<th>GMTA n=18</th>
<th>WMTA n=18</th>
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<td>0.017-0.384</td>
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<tr>
<td>Unit Area (UA)</td>
<td>Mean (SD)</td>
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<td></td>
<td>3.052 (1.194)</td>
<td>3.259 (1.286)</td>
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<td></td>
<td>Range</td>
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<tr>
<td></td>
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<td>1.186-6.408</td>
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<td>Volume per UA†</td>
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<td>0.043 (0.028)</td>
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<td></td>
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<tr>
<td></td>
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<td>0.007-0.095</td>
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</table>
† t-test p-value = 0.994

Figure 8. Setting expansion measured by the slice method demonstrated no significant differences between the expansion of gray and white MTA formulations. Samples are arranged in ascending order of expansion.
Figure 9. Setting expansion of GMTA sample 3 demonstrated by diagraming the surface of the repair material at 0 hours (red line) and 24 hours (blue line). The blue plane on the inset image displays the corresponding slice represented in the graph. The red region is the GMTA repair corresponding to the plotted lines.
Comparison between the two methods demonstrated very high correlation ($r = 0.93$), indicating that both methods of volume change per unit area evaluation are acceptable. The mean difference between the 3D and the slice method for volume change per unit area was 0.0029 (95% confidence interval: -0.001, 0.0069). WMTA sample number 12 appeared to be an aberration, but a sensitivity analysis removing this sample did not alter the results.

![GMTA Expansion by Evaluation Method](image)

**Figure 10.** A comparison of setting expansion of GMTA measured by 3D and Slice demonstrating high correlation ($r = 0.93$).
DISCUSSION

An investigation into the setting expansion of MTA cements in an extracted tooth model has not previously been undertaken. Previous reports have measured the linear expansion of a known quantity of MTA and converted these numbers into percentage increases. While the current study does not provide the ability to measure a percent expansion of the material, the volume change per unit area provides an evaluation of the material properties in a simulated clinical model. In agreement with previous studies utilizing different methodologies (Chng et al., 2005; Islam et al., 2006; Storm et al., 2008), MTA cements expand upon setting according to the current study.

The difference in setting expansion between GMTA and WMTA was not significant in this study, in agreement with the results of Islam et al. and Chng et al., but differing from Storm et al. Variation in testing methodology is likely responsible for demonstrated differences in results. Chng et al. and Islam et al. followed ISO 6876:2001 for the evaluation of dimensional stability; however, this method does not begin to assess linear growth until three times the measured setting time (Chng et al., 2005; Islam et al., 2006). Over 50% of the total setting expansion occurs in the initial 5 hours (Storm et al., 2008), a period that would not be evaluated in this methodology.

Spangberg et al. demonstrated the necessity of preparing materials for testing in the same manner as they are applied clinically (Spangberg, Pascon, 1988). The in vitro methodology utilized in this study was designed to closely approximate the clinical application of MTA cements. The application of the MTA cements to a perforation
created in a tooth was performed to mimic the clinical setting, as was the use of sterile local anesthetic solution for hydration and placement of an intracoronal, moist cotton pellet adjacent to the setting material.

Local anesthetic was chosen as the hydration agent in this study based on the results of the Kogan and Vanderweele studies, and the underlying theme from Spangberg et al.—that materials should be tested in the same form they are used clinically. The ratio of powder to liquid recommended by the manufacturer, measured precisely at 3:1 by mass, was chosen for standardization in the current study. During clinical application, the hydration agent is likely added segmentally during mixing until a desired consistency is achieved, rather than being measured and mixed. Additional studies should be undertaken to determine both the methods being employed clinically and the effects, if any, of varying mixing protocols.

Moist cotton pellet placement has been shown to result in decreased leakage (Matt et al., 2004), and was therefore adopted in this study. Although Storm et al. utilized sterile water to simulate the water uptake from a moist cotton pellet and Hank’s balanced salt solution to simulate the contact between the cements and body fluids (Storm et al., 2008), the application of both the moist cotton pellet and Hank’s to a single sample was not possible. The current study model allowed the application of both fluids simultaneously in an effort to mimic the clinical application.

The potential for an interaction between the surface coating agent, Spotcheck, and the MTA cements exists as a possible source of error in this methodology. Attempts to complete the scanning of the samples by altering the surface with acid etchants or
abrasion prior to scanning was unsuccessful, therefore a comparison could not be made. Uneven coating appeared to be present on the 24 hour scan of WMTA sample 5, and though it did not affect the area of interest this possibility exists. A new methodology that does not require the application of a spray coat for the measurement phase would be preferred.

Figure 11. 0 hour (left) and 24 hour (right) scans of WMTA sample 5. The 24 hour scan demonstrates uneven coating with Spotcheck as a potential limitation of the current model.

An interaction between Hank’s balanced salt solution and MTA cements has been hypothesized to preferentially affect the setting expansion of the gray formulation due to its higher iron content (Storm et al., 2008). In the absence of evidence supporting this hypothesis, Hank’s was deemed a suitable solution with properties similar to the physiologic fluids encountered during clinical use. For future studies, the use of gingival crevicular fluid may further validate the perforation repair model.

Previous studies required contact with the repair material during setting, which may have inhibited its expansion. The setting expansion measured in the current study was not inhibited by surface contact at any point following material placement, including the measurement periods. When applied clinically, however, the periodontium may restrict the setting expansion of the material.
The amount of force exerted on tooth structure by the expansion of a dental material and its consequences are highly material dependent (Ørstavik et al., 2001). Although Orstavik et al. question the need for strict requirements against expansion of materials used to seal the root canal space, his studies involved sealers that would surround gutta-percha or similar obturating materials. The presence of gutta-percha reduces the volume of expanding material placed while absorbing some of the stress generated. Concern regarding excessive expansion of a root end filling or perforation repair material, which is placed in bulk and may cause cracks or fractures (Islam et al., 2006), warrants further study.

The evaluation of setting expansion in the current study demonstrates no significant difference between the gray and white formulations of MTA. Differences in setting expansion have been hypothesized to be responsible for increased leakage associated with WMTA (Storm et al., 2008). Based on the results of the current study, however, differences in setting expansion may not be the source of previously demonstrated differences.
CONCLUSION

The results do not provide evidence to reject the null hypothesis. Under the conditions of this \textit{in vitro} study, no significant difference was demonstrated between the setting expansion of the gray and white formulations of MTA. Further research into the clinical relevance of the observed setting expansion is recommended.
REFERENCES


Bortoluzzi, E A; Araújo, G S; Guerreiro Tanomaru, J M; Tanomaru, M (2007). Marginal


Kakehashi, S; Stanley, H R; Fitzgerald, R J (1965). The effects of surgical exposures of


Stowe, T J; Sedgley, C M; Stowe, B; Fenno, C J (2004). The effects of chlorhexidine gluconate (0.12%) on the antimicrobial properties of tooth-colored ProRoot mineral trioxide aggregate. *Journal of Endodontics* 30 (6), pp. 429-431.


Torabinejad, M; Watson, T F; Pitt Ford, T R (1993). Sealing ability of a mineral trioxide aggregate when used as a root end filling material. *Journal of Endodontics* 19
Tselnik, M; Baumgartner, J Craig; Marshall, J Gordon (2004). Bacterial leakage with mineral trioxide aggregate or a resin-modified glass ionomer used as a coronal barrier. *Journal of Endodontics* 30 (11), pp. 782-784.


## APPENDIX I: CUMULUS DATA TABLE

<table>
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<tr>
<th>Sample</th>
<th>Vol3D</th>
<th>VolSlice</th>
<th>SA3D</th>
<th>SASlice</th>
<th>VperSA3D</th>
<th>VperSASlice</th>
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ADDENDUM

During the thesis defense, there was a good deal of discussion about the linear expansion of the gray and white MTA formulations. The purpose of the following was to estimate linear expansion of the gray and white MTA formulations in the experimental teeth.

Samples were rinsed to remove any Spotcheck coating agent and aligned for sectioning with an IsoCut Wafering Blade on an IsoMet Low Speed Saw (Buehler LTD. Lake Bluff, IL). The samples were sectioned along the long axis of the perforation and an attempt was made to maintain the widest dimension of the MTA perforation repair. Twenty-two samples survived the sectioning procedure with the perforation repair material intact and well-centered for measurement.

An assumption for this phase of the research was that setting expansion occurs equally on each side of the perforation if left unobstructed. Therefore, samples in which the root canal space adjacent to the repair material was obstructed by excess material, cotton pellet, or both, were excluded from measurement. Calculations were performed on fourteen samples. The dimensions of the MTA perforation repair were measured with electronic digital calipers (ST Industries, Inc. St James, MN) and recorded (Table 1). Two measurements were made for the length of the perforation repair material from the surface of the tooth to the root canal space and averaged to give an estimated length of the material.

The “mean depth” was calculated in Cumulus by both the 3D and slice evaluation methods and averaged as well to give and average mean depth. Mean depth is the average
change in surface area for all points within the regions of interest, positive or negative. The mean depth demonstrates the mean distance each point on the surface of the MTA perforation repair expanded from the 0 hour scan to the 24 hour scan.

The average of the mean depth values was divided by the average of the two length measurements for each sample, resulting in the estimated percent linear expansion of the MTA perforation repair (Table 1). The design of the current study did not allow an exact measurement of the linear expansion or volume of material to be performed. The values listed are estimates intended to allow for comparison to previously reported data on the setting expansion of MTA cements. The external surface change was measured and utilized for the estimate, however an assumption of equal expansion on the internal surface would lead to a doubling of the reported values.

The average linear expansion of GMTA is 3.01 ± .0193%, and the average of WMTA is 1.99 ± .00797%. These estimated values are an order of magnitude larger than the mean percent linear setting expansion of GMTA and WMTA in Hank’s balanced salt solution reported by Storm et al. (.68 and .11, respectively). The effect of the observed and estimated setting expansion on tooth structure warrants further study.
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<th>Length 1</th>
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Table 3: Linear expansion of gray and white MTA samples