Abdoul R. Koroni, D.D.S.
Endodontics resident
Office Address
University Of Maryland, Baltimore
650 West Baltimore Department of Advanced Oral Sciences and Therapeutics
Advanced Specialty Education
Baltimore, MD.21201
arkoroni@umaryland.edu
drakoroni@gmail.com

University of Maryland, Baltimore, Certificate in Endodontics	Jul 2022 – Present
University of Maryland, Baltimore, Master of biomedical	May -2025
University of Texas Houston Dental Branch, Endodontics Preceptor,	July 2019-june 2020
University of Texas San Antonio, Certificate A.E.G.D	July1993-june 1994
University of Texas Houston Dental Branch D.D.S	Aug 1989-May 1993

Undergraduate Education:

Texas Southern University, Bachelor of Since in Civil Engineering Sep 1982 – May 1987

Education experience:

University of Texas Department General Practice &Public Health

Clinical Assistance professor		March 2019-May2022
Gulf Family Dental Houston, Texas	Dental General Practice	May 2001-June 2022
Castle Dental Center Houston Texas	Clinical Director	Aug 1998-May 2001

Licensure:

Texas Board of Dental Examiner	Aug 1998-Present
WV Board of Dental Examiner	Feb 20222 -Present

Certifications:

Basic Life Support March 2025-March 2026

Fellowship:

University of Texas Houston Dental Branch Academic Health Career April 2018

Professional Organizations:

American Association of Endodontists April 2016-Present

Research:

Effect of EDTA on the efficacy of NaOCl and Chlor-XTRA on pulp tissue dissolution

Physical and Mechanical Properties of Three Popular Endodontics Sealers. An In Vitro Study

Physical and Mechanical Properties of Three Popular Endodontics Sealers. An In Vitro Study.

by
Abdoul Koroni

Thesis submitted to the Faculty of the Graduate School of the
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1. Introduction

Endodontic treatment is a crucial element of dentistry to eliminate infections from the root canal system. This treatment is dependent on the materials used to seal the root canal[1,2]. An endodontic procedure's success depends on the sealers' quality, performance, and ability to prevent microleakage and entomb remaining microorganisms[3,4]. The focus of this research is on four widely used endodontic sealers: EndoSequence® BC Sealer, NeoSEALER® Flo, EndoCeramic®, and ProRoot MTA® (tooth-colored/white). These sealers were evaluated based on their physicochemical properties, as per International Organization for Standardization (ISO) guidelines, to provide a comprehensive understanding of their performance and suitability for clinical use (6876:2012; Dentistry — Root canal sealing materials).

Endodontic sealers have significantly advanced, transitioning from traditional materials such as zinc oxide-eugenol and epoxy resins to more sophisticated bioceramic sealers[5]. These modern sealers offer superior properties, including enhanced biocompatibility, antimicrobial activity, and improved physical characteristics. A thorough understanding of these properties is fundamental for clinicians to make informed decisions and to provide excellent patient outcomes[5,6].

Endodontic treatment involves critical steps that impact the success of the procedure. Among these steps, the choice and application of the root canal sealer are important [5]. Sealers fill the irregularities and voids within the root canal system, creating a barrier preventing bacteria and other pathogens from infiltrating. The performance of these sealers can directly influence the longevity of the treatment and the prevention of recurrent infections[6,7].

Using ISO 6876:2012 standards, the primary aim of this project was to evaluate the physicochemical properties of three popular bioceramic sealers: EndoSequence® BC Sealer, NeoSEALER® Flo, EndoCeramic®, and ProRoot MTA®. These evaluations were standardized and formed a reliable framework for comparison. This research aimed to comprehensively evaluate their setting time, working time, flowability, dimensional stability, film thickness, and solubility, which contributes to understanding their suitability for clinical use.

1.1. Background

The evolution of endodontic sealers reflects ongoing advancements in dental materials science. Historically, these materials provided satisfactory sealing properties but had limitations regarding biocompatibility and efficiency[5,7].

The introduction of bioceramic sealers represents a significant milestone in the evolution of endodontic materials. Bioceramics are inorganic, non-metallic materials that exhibit excellent biocompatibility and bioactivity[9].

1.2. Historical Development

The journey of endodontic sealers began in the early 20th century with the use of zinc oxide-eugenol, a material known for its antimicrobial properties and ease of use[10]. Epoxy resin-based sealers were developed in the mid-20th century and provided improved sealing ability[5,9]. Each generation of sealer has improved sealing ability, biocompatibility, and clinical performance

The bioceramic materials were initially developed for orthopedic applications. The success of bioceramics in medicine led to their adaptation for dentistry. Bioceramic sealers offer several advantages over traditional materials[5,9,10]. These sealers comprise calcium silicates and other biocompatible compounds that form a chemical bond with the dentin and other root canal filling materials. A bond enhances the sealing ability and durability of the sealer[9–11]. One of the properties of bioceramic sealers is their ability to form hydroxyapatite upon setting. Hydroxyapatite, a naturally occurring mineral in bone and teeth, helps integrate the sealer with surrounding tissue. Bioceramic sealers are also known for their antibacterial properties due to their high pH[9].

Bioceramic sealers have been shown to reduce postoperative sensitivity and enhance periapical tissue healing. Their ease of use and reliable performance have made them a preferred choice for many endodontic practitioners[12–14].

1.3. Types of Endodontic Sealers

There are several endodontic sealers, each with distinct compositions, properties, and mechanisms of action. The main types of endodontic sealers include:

1.3.1 Zinc Oxide-Eugenol Sealers

Zinc oxide-eugenol (ZOE) sealers are composed of zinc oxide powder mixed with eugenol, an oil extracted from cloves. These sealers are known for their good sealing ability, antimicrobial properties, and ease of use. However, they have limitations such as cytotoxicity, solubility, and difficulty in removal when retreatment is needed[5,6].

1.3.2. Resin-Based Sealers

Resin-based sealers are composed of epoxy or methacrylate resins. They adhere to dentin and gutta-percha. They have low solubility, good mechanical properties, and resistance to breakdown. However, they can be hard to handle[15].

1.3.3. Glass Ionomer Sealers

Glass ionomer sealers are composed of glass particles and polyacrylic acid. These sealers release fluoride, which helps prevent recurrent caries and enhances remineralization of the surrounding tooth structure. Glass ionomer sealers are biocompatible and adhere to dentin. Flow and adaptability may be less when compared to other sealers[5].

1.3.4. Silicone-Based Sealers

Silicone-based sealers are known for their biocompatibility and ease of use. They demonstrate minimal shrinkage. Silicone-based sealers have low solubility and are easy to remove if retreatment is needed, but their adhesion to coronal dentin can be lower than resin-based sealers[6,16].

1.3.5 Calcium Hydroxide Sealers

Calcium hydroxide sealers are known for their antimicrobial properties and ability to stimulate hard tissue formation. They release calcium ions, promoting the healing and repair of periapical tissue. These sealers are biocompatible and provide a good seal but are more soluble than other sealer types[5,17].

1.3.6. Bioceramic Sealers

Bioceramic sealers are the latest generation of endodontic sealers. Composed of calcium silicates and other compounds that set in moisture, bioceramic sealers can form a chemical bond with coronal dentin and gutta-percha, providing a seal with low shrinkage[9].

1.4. Root Canal Sealers Under Investigation

1.4.1. EndoSequence BC Sealer

EndoSequence BC Sealer is a premixed, ready-to-use bioceramic sealer that utilizes the moisture in dentinal tubules to initiate its setting reaction. It forms hydroxyapatite upon setting, providing a chemical bond to dentin and bioceramic-coated points. Its high pH contributes to its antibacterial properties. Studies report low solubility, dimensional stability, and favorable setting time[13,14].

1.4.2. NeoSEALER Flo

NeoSEALER Flo is known for its excellent flow properties. Like other bioceramic root canal sealers, NeoSEALER Flo promotes hydroxyapatite formation, contributing to healing and providing a strong seal. It is compatible with cold and warm obturation techniques and is radiopaque[18].

1.4.3. EndoCeramic

EndoCeramic is another new bioceramic sealer used in endodontics. It is designed to provide superior sealing properties, biocompatibility, and ease of use. EndoCeramic sets in moisture, forming a chemical bond with coronal dentin and gutta-percha. It is reported to have low solubility and dimensional stability[9].

1.4.4. ProRoot MTA®

ProRoot MTA® (Mineral Trioxide Aggregate) is a well-established endodontic material known for its biocompatibility and effective sealing properties. It comprises fine hydrophilic particles that set in moisture, forming a solid mass that seals the root canal system. The material is available in a tooth-colored/white formulation. Although it is not used as a sealer, it is included in this project for comparative purposes because it is the most widely researched endodontic material for root end fillings, obturation, and perforation repair. Developed in the 1990s and commercially available for over 25 years, ProRoot MTA® has been extensively studied, with research demonstrating its superior sealing ability, dimensional stability, and biocompatibility. It is arguably the gold standard amongst endodontic materials. Its ability to form hydroxyapatite upon setting enhances its bond with coronal dentin, providing a durable and long-lasting seal[19].

1.5. Physicochemical Properties of Root Canal Sealers

The physicochemical properties of endodontic sealers are critical parameters that influence their clinical handling and performance. These parameters determine how a clinician can work with the material during a root canal procedure, ultimately impacting treatment success[20–22].

Setting time refers to the duration required for the sealer to harden and achieve its final properties. This period is important because it affects the stability of the sealer within the root canal system[23]. A sealer must achieve an appropriate setting time to ensure that it forms an effective seal. A short setting time can be advantageous in reducing the overall treatment time, which can be particularly beneficial in busy clinical settings or when treating patients who may have difficulty sitting through lengthy procedures. However, a very short setting time can also pose challenges. If the sealer hardens too quickly, it may not allow enough time for the clinician to place and adjust the material, which can compromise the treatment's effectiveness[23,24]. On the other hand, a sealer with a long setting time can provide clinicians with more flexibility and control during the procedure. It allows enough time to place the sealer, adjust the filling materials, and ensure a thorough seal. However, a long setting time can delay the completion of the procedure, which may not be ideal in situations where prompt treatment is necessary. Prolonged setting times can also increase the contamination risk if the sealer is exposed to oral fluids before it fully hardens[23,25].

Working time is when the sealer remains workable and can be manipulated within the canal. This parameter is crucial because it determines how long a clinician can effectively work with the material to achieve the desired placement and adaptation within the root canal system[26]. A short working time can be challenging as it may rush the clinician. This rushed application can result in voids, gaps, or uneven sealer distribution.

Inadequate sealing can lead to leakage, reinfection, and ultimately the failure of the root canal treatment[20]. On the other hand, a long working time provides the clinician greater flexibility and control during the procedure. It allows for meticulous placement and adaptation of the sealer. This thorough application is crucial for achieving long-term treatment success[26].

Dimensional stability is a critical property of endodontic sealers, as it determines their ability to maintain their volume and shape over time after setting. A sealer that undergoes shrinkage can create gaps between the filling material and the canal walls. Conversely, expansion may put pressure on the surrounding dentin, potentially leading to fractures or compromising the integrity of the root structure. Ideally, a sealer exhibits minimal dimensional changes to provide a long-term seal[27,28].

Film thickness is another factor influencing the performance of endodontic sealers. A thinner film thickness enhances the sealer's ability to penetrate irregularities and lateral canals, improving the adaptation between the root canal walls and the core filling material. However, a film that is too thin may not provide sufficient coverage to fill gaps effectively, especially in cases with complex canal morphologies. Conversely, an excessively thick film can compromise the stability of the filling. The ideal film thickness should balance optimal flowability and coverage to maximize the effectiveness of the obturation.

Solubility refers to the extent to which a sealer dissolves or degrades when exposed to oral fluids over time. A highly soluble sealer can compromise the seal of the root canal system. This can significantly increase the risk of endodontic failure. Clinically, sealers with low solubility are preferred because they contribute to the integrity of the obturation.

Complete insolubility is not necessarily ideal. Some degree of degradation may facilitate the gradual release of antimicrobial agents incorporated into certain sealers. An optimal balance between low solubility and controlled bioactivity is essential[27].

1.6. Evaluation Methods

The evaluation of the physicochemical properties typically involves standardized tests that measure various properties. These evaluations are essential for determining the sealers' performance and suitability for clinical use. ISO standards provide a framework for these evaluations, ensuring consistency and reliability in the results. Additionally, advanced techniques such as micro-computed tomography (micro-CT) can provide detailed insights into the material's behavior under clinical conditions[29].

1.6.1. ISO Standards[30]

ISO standards specify the requirements for various properties, including setting time, working time, flowability, dimensional stability, film thickness, and solubility. These standards ensure that the materials meet specific criteria for clinical use, providing a basis for comparison and evaluation. The International Organization for Standardization (ISO) has developed a series of standards (e.g., ISO 6876:2012) that outline the methods for testing the physical properties of dental root canal sealing materials. The setting time is determined by observing the transition of the material from a pliable state to a hardened state under controlled conditions. The working time is evaluated by measuring the duration the material remains workable and can be effectively manipulated within the canal. These tests are conducted at specific temperatures and humidity levels to simulate clinical conditions accurately. The solubility of endodontic sealers is assessed by immersing the set material in distilled water for a defined period, typically 24 hours. The weight loss of the material is measured to determine its solubility. Low solubility is desirable as it indicates that the sealer will remain intact and effective over time, providing a long-lasting seal.

Dimensional stability is evaluated by measuring the changes in volume or linear dimensions of the sealer after setting. This property is crucial because any significant expansion or shrinkage can compromise the seal's integrity.

1.6.2. Micro-Computed Tomography (Micro-CT)

Micro-computed tomography (micro-CT) is an imaging technique that allows for non-destructive, three-dimensional analysis of the material's properties. Micro-CT generates high-resolution, three-dimensional images of the sealer within the root canal system. This imaging technique allows for precise visualization of any voids, gaps, or inconsistencies in the filling. These detailed images enable an assessment of the sealer's sealing ability and adaptation to the canal walls. Micro-CT facilitates volumetric analysis of the sealer, quantifying the volume of material used and the extent of its penetration into the canal system. Micro-CT can also monitor dimensional changes in the sealer over time by comparing images taken at different time points. This capability is essential for assessing the long-term stability of the sealer [31].

Evaluation of endodontic sealers involves a combination of standardized tests and advanced imaging techniques to assess their properties and performance. While ISO standards provide a reliable framework for measuring critical parameters, advanced techniques like micro-CT offer detailed insights into its clinical suitability. It is essential to consider and compare various sealers' mechanical and physical characteristics to determine their potential in specific conditions and situations. This comprehensive approach helps clinicians select the most appropriate sealer rather than simply identifying a universally superior product.

2. Materials and Methods

The physical properties of four widely used endodontic sealers—EndoSequence® BC Sealer, NeoSEALER® Flo, EndoCeramic®, and ProRoot MTA®—were evaluated following ISO 6876:2012 standards[30]. These evaluations included setting time, working time, flowability, dimensional stability, film thickness, and solubility. Each sealer was prepared according to the manufacturer's instructions under standardized laboratory conditions. The tests were conducted at a controlled temperature of 23 ± 2°C and a relative humidity of 50 ± 10%, as outlined in ISO 6876:2012. For sealers requiring moisture for setting, additional water (0.02 mL per 0.02 g) was added. Before testing, all materials were thoroughly mixed to ensure homogeneity and applied to the specimens using sterile instruments to avoid contamination.

2.1. Setting Time

The setting time of each sealer was determined using a Gilmore needle apparatus with an indenter weighing (100 ± 0.5) g. The indenter featured a flat cylindrical tip with a diameter of (2 ± 0.1) mm and a cylindrical length of at least 5 mm, with the end plane perpendicular to the longitudinal axis (Figure 1).

Cylindrical molds (10 mm in diameter and 2 mm in height) were preconditioned by storing them at 37 ± 1°C and 95–100% relative humidity for 24 hours. The freshly mixed sealer was prepared according to the manufacturer's instructions and placed into the preconditioned molds.

The indenter was carefully lowered vertically onto the horizontal surface of the sealer. After each use, the indenter tip was cleaned, and the operation was repeated until no visible indentation was observed. Measurements were conducted in triplicate for each sealer.

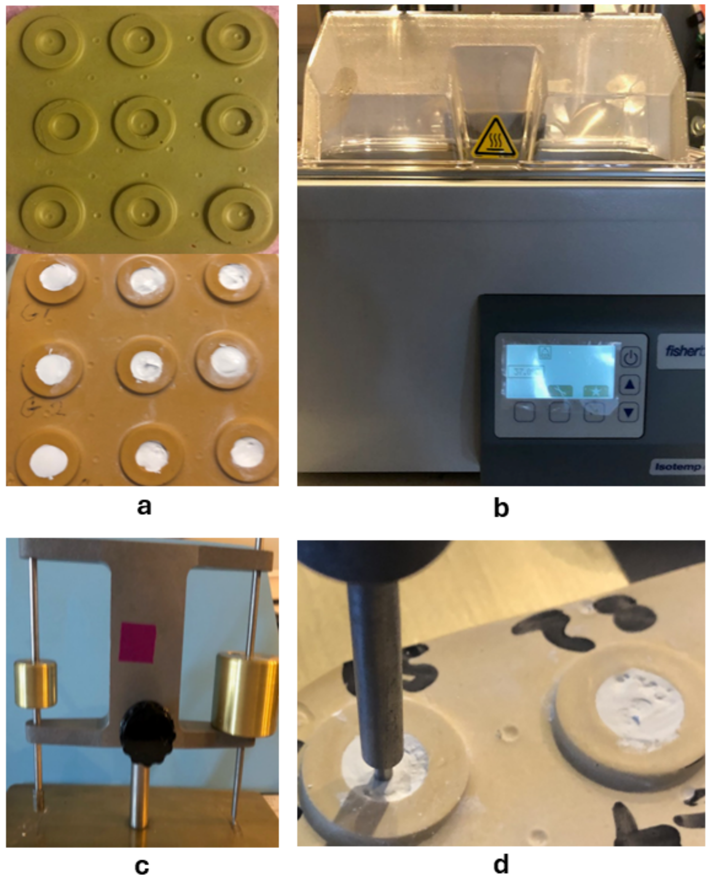


Figure 1. Representative images of the materials and apparatus used to determine the setting time of sealers (a) cylindrical molds (10 mm in diameter and 2 mm in height) before and after filling with the sealer, (b) cabinet maintained at 37 ± 1°C and 95–100% relative humidity for preconditioning and storage, (c) Gilmore needle apparatus with a 100 g indenter, and (d) indenter in contact with the set sealer during the final measurement.

2.2. Working Time

The working time of the sealer was determined using two glass plates (40 mm × 40 mm, approximately 5 mm thick) and a weight of approximately 100 g. One glass plate weighed approximately 20 g.

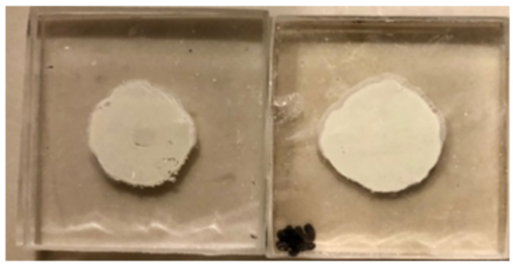
A graduated syringe, designed to deliver (0.05 ± 0.005) mL of freshly mixed sealer, was used to place the sealer on the glass plate. Using the working time stated by the manufacturer as a guideline, the test was repeated at increasing intervals from the start of mixing until the setting time stated by the manufacturer. For each measurement, a freshly mixed sealer was used. The working time was recorded when the specimen’s diameter decreased by 10% compared to the initial flow value.

2.3. Flowability

The flowability of the sealers was evaluated using two glass plates (40 mm × 40 mm and approximately 5 mm thick). One glass plate weighed approximately 20 g, and an additional weight of approximately 100 g was used to achieve a total load of (120 ± 2) g.

A freshly mixed sealer, prepared according to the manufacturer's instructions, was placed using a graduated syringe to deliver (0.05 ± 0.005) mL onto the center of one glass plate. At (180 ± 5) seconds after the start of mixing, the second glass plate was placed centrally on top of the sealer, followed by the additional weight to apply the total load. Ten minutes after the start of mixing, the weight and top plate were removed, and the maximum and minimum diameters of the compressed sealer disc were measured using a digital caliper (Figure 2). Their mean was recorded if the diameters differed by no more than 1 mm. The test was repeated if the diameters differed by more than 1 mm. Three measurements were done for each sealer to ensure compliance with the required specifications.

a



b

Figure 2. Representative images of the flowability testing process (a) freshly mixed sealer placed between two glass plates with a total load of 120 ± 2 g applied, and (b) the compressed sealer disc after removing the top glass plate and weight, showing the resulting spread for diameter measurement.

2.4. Dimensional Stability

Dimensional stability was assessed using 12 split cylindrical molds with an internal diameter of 6 mm and a height of 12 mm. The molds' internal surfaces were sprayed with a releasing agent to facilitate the removal of the sealer after setting.

A polyethylene sheet was placed between the base glass plate and the mold, and another was used to cover the top of the mold. A freshly mixed sealer, 2 g of sealer with 0.02 mL of water, was added to the mold until it was slightly overfilled. Five minutes after mixing, the filled molds were placed between two glass plates and secured with 25 mm C-clamps.

The molds were then stored in a cabinet at 37 ± 1°C and 95–100% relative humidity. The placement time in the cabinet was recorded, and after 24 hours, the specimens were removed. The ends of the specimens were ground flat using 600-grit wet sandpaper by drawing the mold back and forth across the abrasive surface.

The specimens were then carefully unmolded, and three measurements of the distance between the flat ends were taken for each sample using a digital caliper with an accuracy of 10 micrometers (Figure 3). After the initial dimensions were recorded, the specimens were immersed in separate wells containing distilled water maintained at 37 ± 1°C. Dimensional measurements were performed after 15 and 30 days, and dimensional changes were expressed as a percentage of the initial measurements.

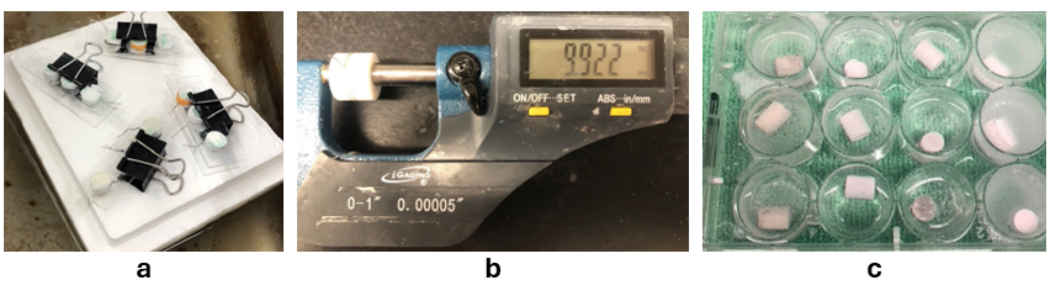
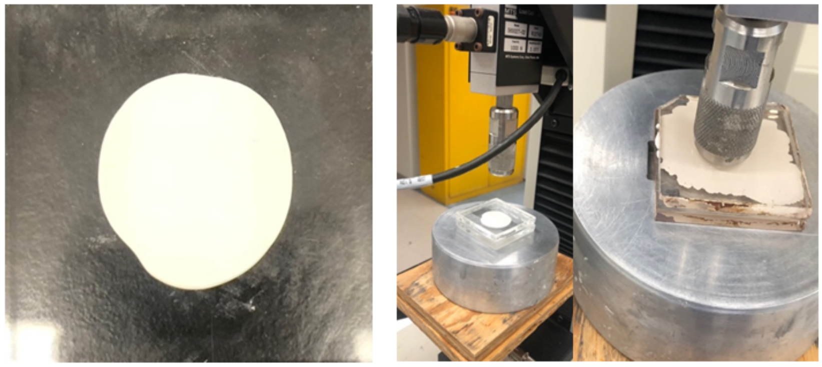


Figure 3. Representative images of the dimensional stability testing process (a) cylindrical molds filled with freshly mixed sealer, placed between glass plates with polyethylene sheets, and secured with 25 mm C-clamps, (b) sealer cylinder being measured using a digital caliper gauge for initial dimensions, and (c) sealer cylinders submerged in distilled water in 12-well plates for remeasurement after 15 and 30 days.

2.5. Film Thickness

Film thickness was measured using two flat glass plates, each with a minimum uniform thickness of 5 mm and a contact surface area of approximately (200 ± 10) mm^2. The combined thickness of the two glass plates in contact was measured using a digital caliper gauge with an accuracy of 1 μm before the experiment.

A portion of freshly mixed sealer was placed at the center of one glass plate. After (180 ± 10) seconds from the start of mixing, the second glass plate was placed centrally over the sealer. A load of (150 ± 3) N (newtons) was applied vertically to the top plate using a loading device, ensuring the sealer filled the area between the plates. At 10 minutes from mixing, the combined thickness of the two glass plates and the sealer was measured using the micrometer. The thickness of the sealer film was calculated by subtracting the thickness of the glass plates from the total measured thickness. Three measurements were taken, using the same plates for all samples, and the width of the glass plates was measured in three different areas to ensure consistency.



a b

Figure 4. Representative images of the film thickness testing process (a) the second glass plate placed centrally over the sealer (180 ± 10 seconds after mixing) on the first glass plate, and (b) a load of (150 ± 3) N being applied vertically to the top plate using a loading device to ensure uniform compression of the sealer film.

2.6. Solubility

Solubility testing was conducted using two split-ring molds with an internal diameter of (20 ± 1) mm and a height of (1.5 ± 0.1) mm. Each mold was placed on a flat glass plate lined with a polyethylene sheet (50 ± 30 µm thick). A freshly mixed sealer, prepared by combining 2 g of material with 0.02 mL of water, was used to fill the molds slightly in excess. A second glass plate lined with a polyethylene sheet was pressed on top of the molds, and the setup was stored in a cabinet maintained at 37 ± 1°C and ≥95% relative humidity for 24 hours. For the NeoSEALER® Flo and EndoSequence® BC Sealer groups, the ISO standard procedure was modified to allow these sealers to set for a more extended period to ensure they are fully set before proceeding with further steps of the solubility test.

After setting, flash and irregularities were carefully removed from the periphery of the specimens. Each specimen's initial mass (W1) was determined to the nearest 0.001 g using a precision scale. Specimens were then placed in shallow glass jars containing 50 mL of distilled water (ISO 3696:1987 grade 3), and the jars were stored in the cabinet at 37 ± 1°C and ≥95% relative humidity for 24 hours. After immersion, the specimens were removed and washed with 2–3 mL of fresh distilled water, recovering the washings in the shallow dish. The glass jars, with the water and recovered washings, were placed in an oven maintained at 110 ± 2°C to evaporate the water completely. The jars were then cooled, wiped with 70% alcohol, and weighed thrice to determine their final mass (W2). The percentage of mass loss was calculated using the formula:

$$\text{Solubility (\%)} = \frac{W1}{W1-W2} \times 100$$

To ensure consistency and accuracy, the same glass jars were used for each test group from start to finish. All procedures were conducted while wearing gloves to prevent contamination.

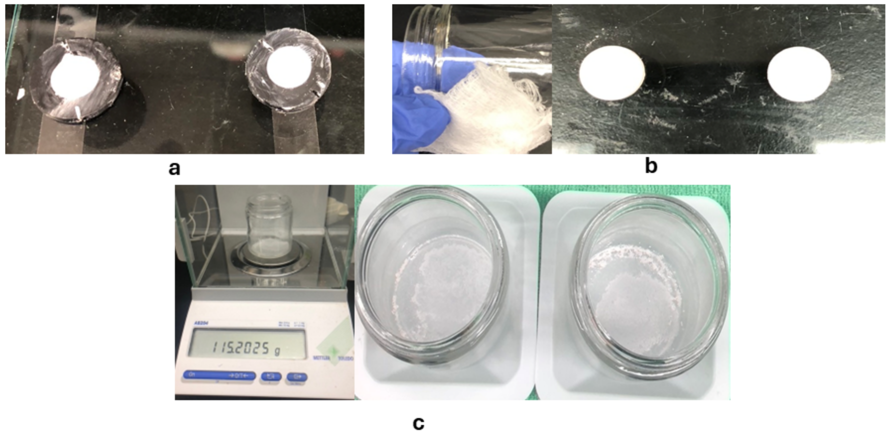


Figure 5. Representative images of the solubility testing process (a) set specimens after removing flash and irregularities from the periphery, (b) cleaning the glass jars with 70% alcohol and placing the specimens for initial weight measurement, and (c) weighing the jars with residual particles after water evaporation to determine the final weight.

2.7. Statistical Analysis

All tests were conducted in triplicate to ensure the reliability and reproducibility of the results. Shapiro-Wilk test was performed to confirm the normality and equal variance of data. One-way analyses of variance (ANOVA) and Tukey comparison tests were performed to detect the significant effects of the dependent variables. Statistical significance was set at $p < 0.05$, and results were reported as mean ± standard deviation. GraphPad Prism software was used for statistical analysis.

3. Results

3.1. Setting Time

Marked differences in the setting times of the evaluated sealers were observed (Figure 6). EndoSequence® BC Sealer exhibited the longest setting time at 1428.67 ± 15.34 minutes, while ProRoot MTA® had the shortest at 251.33 ± 9.28 minutes. NeoSEALER® Flo and EndoCeramic® were intermediate in performance. These differences were statistically significant ($p < 0.001$). The extended setting time of EndoSequence® BC Sealer can be attributed to its bioceramic formulation, which utilizes moisture for a slow hydration reaction. Conversely, ProRoot MTA®'s quick setting time makes it particularly suitable for urgent dental procedures where time efficiency is critical. These findings highlight the variable clinical applications of sealers based on setting time.

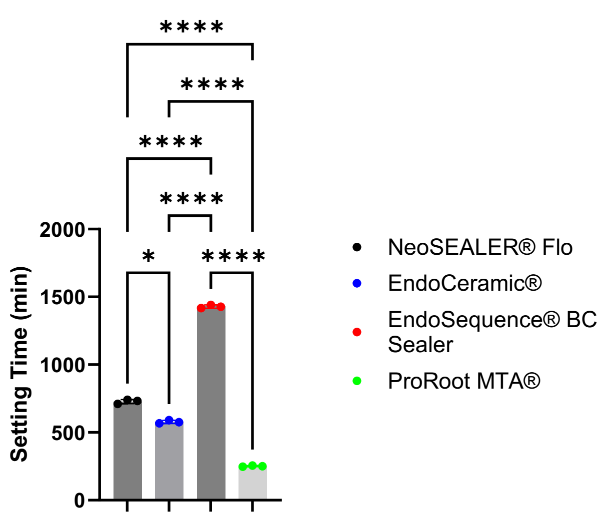


Figure 6. Bar graph representing the setting times (minutes) of the root canal sealers, performed in triplicates. Data are presented as Mean ± SD. Statistically significant differences were observed between groups, with * $p < 0.05$ and **** $p < 0.0001$. EndoSequence® BC Sealer exhibited the longest setting time, while ProRoot MTA® had the shortest.

3.2. Working Time

Working time measurements across the sealers demonstrated interesting findings. While most sealers showed no significant differences in their working times ($p > 0.05$), ensuring flexibility during application regardless of the material used, a notable exception was observed. EndoSequence® BC Sealer exhibited a significantly longer working time compared to ProRoot MTA® ($p < 0.05$) (Figure 7). This distinction highlights potential practical implications, as the extended working time of EndoSequence® BC Sealer may offer enhanced handling benefits during clinical procedures where longer manipulation periods are advantageous. By contrast, ProRoot MTA®, with its comparatively shorter working time, might be better suited for applications requiring quicker setting characteristics. These differences underscore the importance of selecting a sealer based on the specific procedural requirements and clinician preferences.

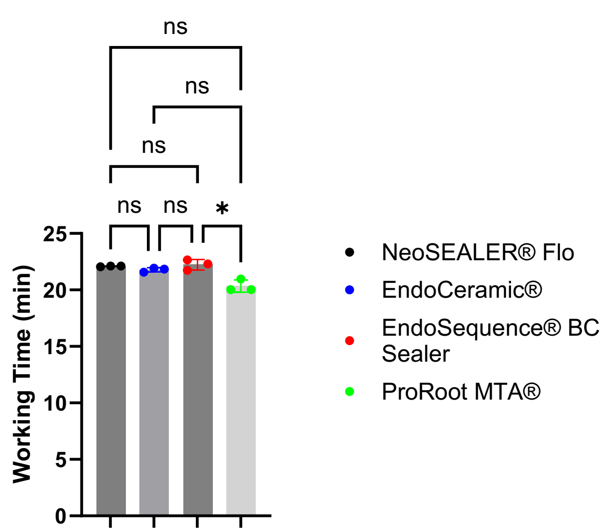


Figure 7. Bar graph representing the working times (minutes) of the root canal sealers, performed in triplicates**.** Data are presented as Mean ± SD. While most sealers showed no significant differences in working time ($p > 0.05$), EndoSequence® BC Sealer exhibited a significantly longer working time compared to ProRoot MTA® ($p < 0.05$)

3.3. Flowability

The sealers also met ISO 6876:2012 standards for flowability, exceeding the minimum threshold of 20 mm. Among the sealers, EndoCeramic® displayed the highest flow value (25.17 ± 0.42 mm). Furthermore, ProRoot MTA® demonstrated significantly lower flowability compared to all other groups, with a p-value of less than 0.05 for EndoCeramic® and less than 0.01 for NeoSEALER® Flo and EndoSequence® BC Sealer. No significant differences in flowability were observed among EndoCeramic®, NeoSEALER® Flo, and EndoSequence® BC Sealer ($p > 0.05$) (Figure 8). The enhanced flowability of EndoCeramic®, attributed to its optimized particle size and viscosity, facilitates comprehensive root canal filling, reducing the likelihood of voids or gaps. In contrast, the comparatively lower flowability of ProRoot MTA® may limit its effectiveness in penetrating complex anatomical features, such as lateral canals. These findings emphasize the critical role of flowability in material selection for optimal clinical outcomes.

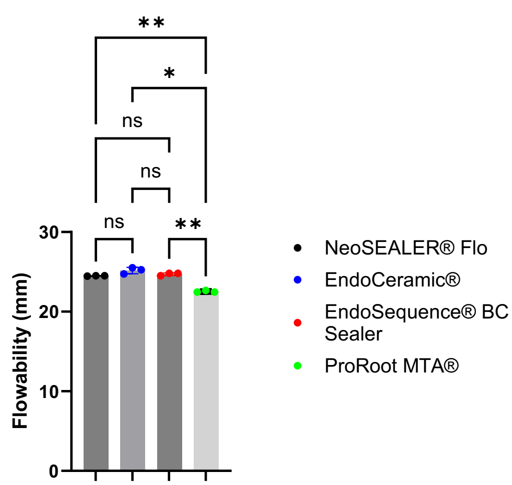


Figure 8. Bar graph representing the flowability (mm) of the root canal sealers, performed in triplicates. Data are presented as Mean ± SD. All sealers exceeded the ISO 6876:2012 minimum threshold of 20 mm. EndoCeramic® exhibited the highest flowability, while ProRoot MTA® showed significantly lower flowability compared to all other groups * $p < 0.05$ and ** $p < 0.01$.

3.4. Dimensional Stability

The results revealed minimal dimensional changes among all sealers, with no significant differences observed between the groups both after 15 days and 30 days ($p > 0.05$) (Figure 9). These results confirm that all sealers adhere to ISO standards for dimensional stability, ensuring their reliability in maintaining a stable seal over time. The findings suggest that factors such as water absorption during the setting phase, which might have been a concern for some materials, did not result in statistically significant volumetric changes within the study period. This consistent performance across the sealers underscores their suitability for preventing microleakage and preserving the integrity of the root canal seal, regardless of the material selected.

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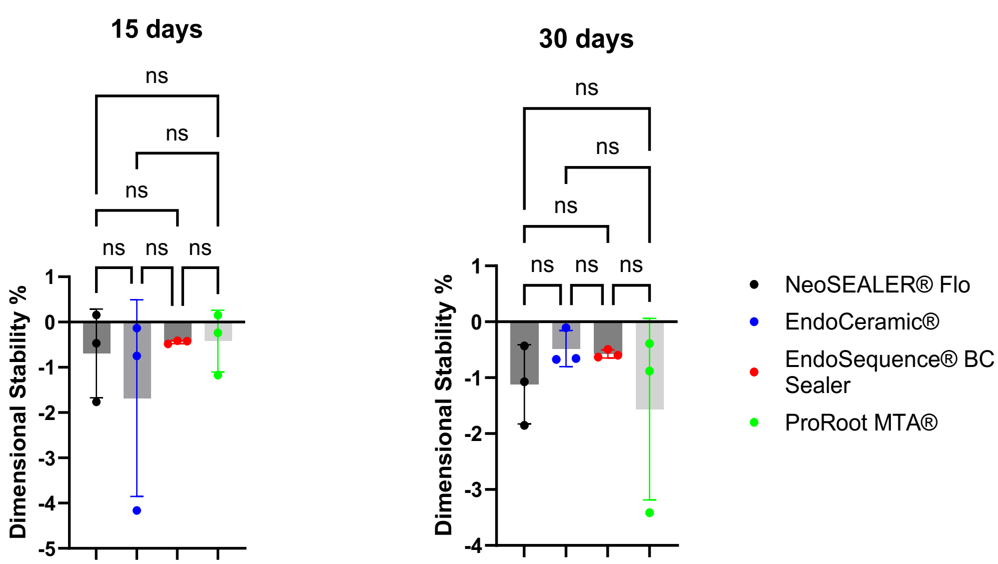

Figure 9. Bar graph representing the dimensional stability (% change) of the root canal sealers over 15 and 30 days, performed in triplicates. Data are presented as Mean ± SD. No significant differences in dimensional changes were observed between the groups at either time point ($p > 0.05$).

3.5. Film Thickness

Film thickness varied across the sealers, with ProRoot MTA® exhibiting the greatest value at 35.67 ± 1.23 µm, significantly higher than the others ($p < 0.001$). The remaining sealers—EndoSequence® BC Sealer, NeoSEALER® Flo, and EndoCeramic®—showed comparable results ($p > 0.05$) (Figure 10). While a higher film thickness in ProRoot MTA® ensures robust sealing in large spaces, its potential limitations in achieving precise applications in narrow canals should be considered.

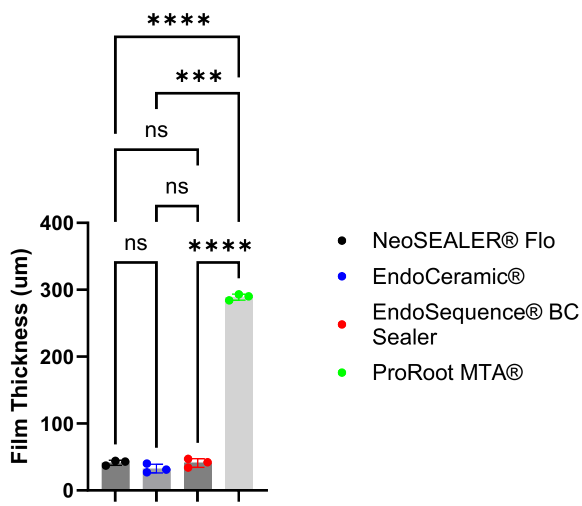

Figure 10. Bar graph representing the film thickness (µm) of the root canal sealers, performed in triplicates. Data are presented as Mean ± SD. ProRoot MTA® exhibited the largest film thickness, significantly higher than the other sealers *** $p < 0.001$ and **** $p < 0.0001$. No significant differences were observed among other groups ($p > 0.05$).

3.6. Solubility

Solubility tests revealed significant variations among the sealers. ProRoot MTA® exhibited the lowest solubility at 2.47%, which was significantly lower than NeoSEALER® Flo (10.46%) and EndoSequence® BC Sealer (9.90%) ($p < 0.01$).

However, the solubility of ProRoot MTA® was not significantly different from that of EndoCeramic® (3.02%). EndoCeramic® showed significant lower solubility comparing to EndoSequence® BC Sealer ($p < 0.05$) but not statistically different from NeoSEALER® Flo (Figure 11). These results emphasize the superior stability of ProRoot MTA® and EndoCeramic® compared to NeoSEALER® Flo and EndoSequence® BC Sealer, which may enhance their durability and resistance to degradation in the root canal environment. While the higher solubility observed in NeoSEALER® Flo and EndoSequence® BC Sealer may contribute to bioactivity, it also raises potential concerns regarding long-term performance.

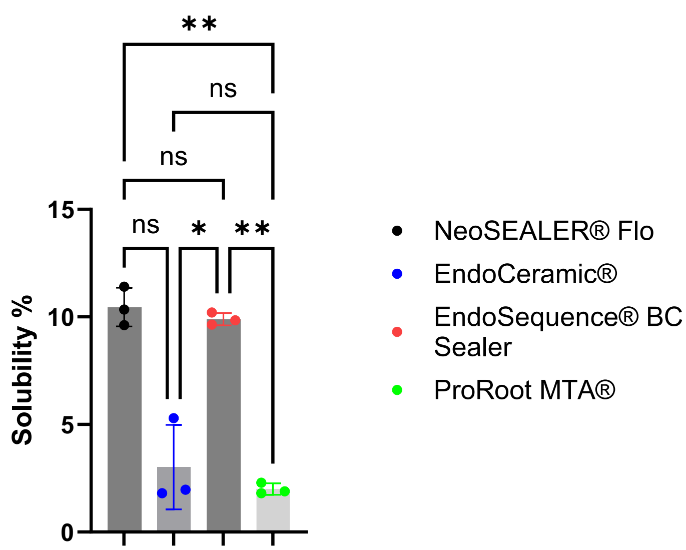

Figure 11. Bar graph representing the solubility (%) of the root canal sealers, performed in triplicates. Data are presented as Mean ± SD. ProRoot MTA® and EndoCeramic® showed the lowest solubility, significantly lower than EndoSequence® BC Sealer * $p < 0.05$ ** $p<0.01$. ProRoot MTA® also showed statistically different solubility compared to NeoSEALER® Flo. other groups showed no significant difference in solubility ($p > 0.05$).

4. Discussion and Conclusion

The physicochemical properties of Root canal sealers, including setting time, working time, flowability, dimensional stability, solubility, and film thickness, critically influence clinical outcomes of an endodontic treatment[6]. This study's findings highlight the nuanced performance of different sealers, offering insights into their optimal clinical applications.

Differences in setting times among the sealers underscore their diverse clinical utilities[25]. EndoSequence® BC Sealer exhibited the longest setting time, significantly exceeding the others, which can be attributed to its bioceramic formulation that relies on moisture-driven hydration[5]. This extended setting time is advantageous in procedures requiring prolonged working durations, ensuring precise placement and adaptation. In contrast, ProRoot MTA®'s rapid setting time makes it ideal for urgent cases, such as perforation repair, where time efficiency is paramount. NeoSEALER® Flo and EndoCeramic® offer intermediate setting times, balancing efficiency and handling flexibility. These findings align with the need for tailored sealer selection based on procedural demands, as longer or shorter setting times can significantly impact clinical workflows.

The working time of sealers determines their maneuverability during application. While no significant differences were observed among most sealers, EndoSequence® BC Sealer had a significantly longer working time than ProRoot MTA®. This extended working time enhances its utility in intricate procedures requiring prolonged manipulation. Conversely, the shorter working time of ProRoot MTA® is better suited for quick applications, particularly in challenging clinical scenarios where time constraints are a concern[9]. These observations highlight the importance of aligning sealer properties with the complexity and duration of the procedure.

Flowability is another critical parameter for achieving comprehensive canal filling, especially in complex anatomical structures. All tested sealers exceeded ISO 6876:2012 standards for flowability[30]. EndoCeramic® demonstrated the highest flow value, significantly outperforming ProRoot MTA®, which exhibited the lowest. The superior flowability of EndoCeramic® facilitates thorough filling of intricate canal spaces, minimizing voids and enhancing sealing efficiency. NeoSEALER® Flo and EndoSequence® BC Sealer also displayed satisfactory flowability, ensuring adaptability to canal anatomy[9,13]. In contrast, ProRoot MTA®'s lower flowability may limit its application in cases requiring extensive penetration into lateral canals, emphasizing the need for careful material selection based on canal complexity.

Dimensional stability is essential to maintaining an effective seal and preventing microleakage[27]. This study found no significant differences in dimensional changes among the sealers after 15 and 30 days, indicating that all materials adhered to ISO standards. This consistency underscores their reliability in preserving the integrity of the seal over time. Notably, the lack of significant volumetric changes suggests that water absorption during the setting phase did not adversely affect sealers, supporting their suitability for long-term clinical use[27,32].

Film thickness impacts the adaptability and sealing capability of root canal sealers. ProRoot MTA® exhibited the highest film thickness, significantly greater than the other sealers. This characteristic makes it well-suited for cases involving wide canal spaces, where a robust sealer layer is beneficial. However, its higher thickness may challenge achieving precision in narrower canals. The other sealers demonstrated comparable film thicknesses, offering versatility across a broader range of clinical scenarios.

Solubility influences the longevity and bioactivity of sealers[27,28,33]. ProRoot MTA® exhibited the lowest solubility, significantly outperforming EndoSequence® BC Sealer, while no significant differences were observed between EndoSequence® BC Sealer and NeoSEALER® Flo. The low solubility of EndoCeramic® enhances its stability and resistance to degradation, making it suitable for long-term treatments. In contrast, the higher solubility observed in NeoSEALER® Flo and EndoSequence® BC Sealer contributes to bioactivity, promoting hydroxyapatite formation and periapical healing. However, this bioactivity must be weighed against potential concerns regarding long-term structural integrity.

4.1. Clinical Implications and Future Directions

This study's findings emphasize the importance of matching sealer properties to clinical requirements. For example, EndoCeramic®'s superior flowability and low solubility make it ideal for complex canal systems requiring long-term stability. EndoSequence® BC Sealer, with its extended setting and working times, is better suited for procedures demanding prolonged manipulation. ProRoot MTA®'s rapid setting time and high film thickness support its application in urgent treatments and large canal spaces, while NeoSEALER® Flo offers a balance of bioactivity and flowability for intricate anatomical configurations[18].

Further research is needed to investigate the long-term clinical performance of bioceramic sealers under varying environmental and procedural conditions. Advanced imaging techniques, such as micro-CT and nanomechanical testing, could provide deeper insights into the interactions between sealer properties and clinical outcomes. Additionally, standardizing testing methodologies across studies would enhance the comparability of results, facilitating evidence-based decision-making in endodontics.

5. Conclusion

This study highlights root canal sealers' diverse properties and performance, emphasizing their unique strengths and limitations. By comparing EndoSequence® BC Sealer, NeoSEALER® Flo, EndoCeramic®, and ProRoot MTA®, the findings provide valuable guidance for clinicians in optimizing treatment outcomes. Aligning sealer selection with procedural requirements and patient-specific needs ensures the long-term success of endodontic treatments.

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