T.C.
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COMPARISON OF THE QUALITY OF THE CANAL FILLINGS PERFORMED USING BIOCERAMIC AND RESIN-BASED ROOT CANAL SEALERS AND THE BOND STRENGTH OF THE SEALERS

DOCTORAL THESIS

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This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by Administrative Board of Institute with decision dated 12.06.2018 and numbered 2018/10-89.

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

08.06.2018

Serpil Terzioğlu

DEDICATION

This thesis is dedicated to:

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I dedicate this research.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	Percent
°C	Degrees Celsius
µA	Microamps
et al	Friends
Ca++	Calcium
EDTA	Ethylenediaminetetraacetic acid
kV	Kilovolt
Micro-CT	Microcomputed tomography
mm	Milimeter
MPa	Megapascals
ms	Milisecond
MTA	Mineral Trioxide Aggregate
NaOCl	Sodium Hypochlorite
OH^{-}	Hydroxyl Ion
r	Radius
SEM	Scanning Electron Microscope
SS	Standard deviation

ABSTRACT

Terzioğlu, S. (2018). Comparison of the quality of the canal fillings performed using bioceramic and resin-based root canal sealers and the bond strength of the sealers.

For a successful root canal treatment, the canal system should be filled as three dimensional without any leakage in order to preserve the level of disinfection achieved after the process of shaping and irrigation of the root canal system and to prevent the passage of bacteria through the canal. A better leak-proof seal can be provided by preventing the formation of voids in the root canal by means of bonding sealers canals to dentin and gutta-perka. In this study, it was aimed to compare the presence of void space in canals filled with the method of lateral condensation by using newly developed bioceramic canal sealers and resin-based canal sealers frequently used clinically by micro-CT and to evaluate the adhesion of canal sealers to dentin by push-out test. In the study, 64 extracted, single rooted and single canal human mandibular premolars were used. All teeth were shaped by using the Protaper Universal rotary files. The teeth were divided into 4 groups, each containing 16 teeth. Root canals were filled with AH plus, MM seal, Endosequence BC sealer and BioRoot RCS canal sealers by using cold lateral condensation method. Teeth having filled canals were scanned in high-resolution micro-CT and the space volumes in the canals were calculated. In the second phase of the study, teeth were embedded in the acrylic resin by using roller molds. After that, sections of 1mm thickness were taken from the teeth. Instron device was used for the measurement of bond strength of canal sealers to dentin. The push-out force was applied until the failure occurred in the joint of the canal filling to the dentin and the values obtained were recorded. The data were analyzed in PC using SPSS 25.0 (Statistical Packages of Social Sciences) program. As a result, none of the used root canal sealers provide a void-free canal filling. When all groups were evaluated within themselves, it has been observed that the void space volume in the apical third was less than the volume in coronal and middle thirds. While there was no statistically significant difference in the volume of the voids found in the entire root among the canal sealers which were used ($p > 0,05$), the highest void volume in the entire root was found in the MM Seal group (1.81%) and the least void volume was found in

Endosequence BC sealer group (1,11%).The lowest values of bond strength were found statistically significant in the MM Seal group. There was no statistically significant difference among the bond strength values of AH Plus, Endosequence BC Sealer and BioRoot RCS canal sealer.

Keywords: micro-CT, push-out test, bioceramic canal sealer

ÖZET

Terzioğlu, S. (2018). Biyoseramik ve rezin esaslı kanal dolgu patları kullanılarak yapılan kanal dolgularının kalitesinin ve patların bağlanma dayanımının karşılaştırılması. Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü, Endodonti ABD. Doktora Tezi. İstanbul.

Başarılı bir kök kanal tedavisi için kök kanal sisteminin şekillendirme ve irrigasyon işlemlerinden sonra elde edilen dezenfeksiyon seviyesini korumak ve bakterilerin kanaldan geçişine engel olmak için kanal sistemi sızdırmaz bir şekilde, üç boyutlu olarak doldurulmalıdır. Kanal patlarının dentine ve güta-perkaya bağlanması ile kök kanal dolgusunda boşluklar oluşması önlenerek daha iyi bir sızdırmazlık oluşturulması sağlanabilir. Bu çalışmada yeni geliştirilen biyoseramik içerikli kanal patları ve klinikte sık kullanılan rezin esaslı kanal patları kullanılarak lateral kondensasyon yöntemiyle doldurulan kanallarda boşluk alan varlığının micro-CT ile karşılaştırılması ve kanal patlarının dentine olan bağlanmalarının push-out testi ile değerlendirilmesi amaçlanmıştır. Çalışmada 64 adet çekilmiş, tek köklü ve tek kanallı, insan alt küçük azı dişleri kullanıldı. Bütün dişler, Protaper Universal döner eğeleri kullanılarak şekillendirildi. Dişler, her biri 16 diş içeren 4 gruba ayrıldı. Kök kanalları AH plus, MM seal, Endosequence BC sealer ve BioRoot RCS kanal patlarıyla soğuk lateral kondensasyon yöntemi ile dolduruldu. Kanal dolumları tamamlanan dişler yüksek çözünürlüklü mikro-CT cihazında taranarak, kanalda bulunan boşluk hacimleri hesaplandı. Çalışmanın ikinci aşamasında, dişler silindir kalıplar kullanılarak akrilik rezin içerisine gömüldü. Daha sonra dişlerden 1 mm kalınlığında kesitler alındı. Kanal patlarının dentine bağlanma dayanımlarının ölçümü için Instron cihazı kullanıldı. Push-out kuvveti, kanal dolgusunun dentine bağlantısında başarısızlık oluşana kadar uygulandı ve elde edilen değerler kaydedildi. Veriler bilgisayarda SPSS 25,0 (Statistical Packages of Social Sciences) programı kullanılarak analiz edildi. Sonuç olarak, kullanılan kök kanal patlarının hiçbiri boşluksuz bir kanal dolgusu sağlayamamaktadır. Bütün gruplar kendi içlerinde değerlendirildiğinde apikal üçlüde tespit edilen boşluk hacminin koronal ve orta üçlülerden az olduğu gözlenmiştir. Kullanılan kanal patları arasında tüm kökte tespit edilen boşluk hacimleri açısından istatistiksel olarak anlamlı bir faklılık olmamakla ($p>0,05$) beraber tüm kökte en fazla boşluk hacmi MM Seal grubunda (%1,81), en az boşluk hacmi Endosequence BC sealer grubunda (%1,11) tespit edilmiştir. Bağlanma dayanımı değerlerinde istatistiksel olarak anlamlı şekilde en düşük sonuçlar MM Seal grubunda tespit edilmiştir. AH Plus, Endosequence BC Sealer ve BioRoot RCS kanal patlarının bağlanma dayanımı değerleri arasında istatistiksel olarak anlamlı bir fark bulunmamıştır.

Anahtar kelimeler: micro-CT, push-out testi, biyoseramik kanal patı

1. INTRODUCTION AND PURPOSE

Successful root canal treatment is achieved by appropriately shaping the root canal system and filling the canal coronal to the apical foramen hermetically in a dimensionally stable manner using a biocompatible canal filling material after elimination of pathogenic organisms (1, 2).

The aim of endodontic treatment is to prevent apical periodontitis, which is an inflammatory process. Residual irritants are trapped in the canal when the root canals are filled in a three-dimensional, hermetic manner, eliminating potentially infectious cavities. Thus, the passage of irritants into periradicular tissues is prevented. For this reason, three-dimensional root canal filling is important in preventing endodontic infections (3, 4). Insufficient canal filling was observed in 58% of the teeth with disease after endodontic treatment (5).

There are several studies in the literature that use different test techniques in evaluating the homogeneity of root canal fillings such as dye penetration, fluid transport, microbial leakage and section analysis. However, there is insufficient information on the detection of void spaces (6, 7). It has been reported that the use of Micro-CT does not exhibit the disadvantages of the general techniques used in the evaluation of root canal filling since it does not cause any root damage (8).

In root canal fillings, root canal sealer or gutta-percha use as canal filling material has been accepted as the gold standard (9). When gutta-percha is used without sealer, the connection to the canal walls fails and voids are formed (10).

When gutta-percha is used alone, root sealer is required to firmly attach to the gutta-percha and dentin surface due to the fact that attachment of gutta-percha to the dentin surface is unsuccessful (11). Formation of voids is prevented as canal sealer is attached to the dentin and gutta-percha, which can provide a better seal and maintain the integrity of the canal filling during preparation of post cavity (12, 13).

Adhesion is defined as the joining and sticking of two different surfaces and refers to the binding that occurs as a result of forces acting between two surfaces. One of the important properties that must be found in an ideal canal filling is that the material needs to show good adhesion. One of the methods used to evaluate the bonding of root canal sealers to the canal wall is push-out tests (14).

Epoxy resin-containing sealers are commonly preferred because of their low solubility, and good apical coverage and dentin bonding (15).

Recently, bioceramic-based canal sealers containing mineral trioxide aggregate and calcium silicate have been developed. The advantage of these new sealers is their bioactive properties (16). Bioceramic-based canal sealers do not shrink after being hardened as in resin-based sealers and do not produce any toxic effects on fibroblasts (17).

Therefore, the aim of this study was to compare the presence of void spaces in canals filled by lateral condensation method with bioceramic and resin-based canal sealers using Micro-CT and evaluate the bonding of canal sealers to the dentin by push-out tests.

2. LITERATURE REVIEW

2.1. Root Canal Filling Materials

The desired characteristics of an ideal root canal filling material are as follows:

1. Should be antibacterial,

2. Should not irritate periapical tissues,

3. Should be sterile or can be sterilized,

4. Should be dimensionally stable,

5. Should not stain dental tissues,

6. Should be easy to use,

7. Should be radioopaque,

8. Should not be affected by tissue fluids,

9. Should not be toxic,

10. Should show easy adhesion with canal walls,

11. Should have good fluidity,

12. Should not exhibit shrinkage in the canal,

13. Should support root structure,

14. Should be easily removed from the canal when necessary,

15. Should have a long operation time and be cheap,

16. Be able to cover the canal laterally and apically.

Gutta-percha cones are the most preferred root canal filling materials today. They provide apical control of the canal fill and can adapt to root canal irregularities (18).

Gutta-percha is a natural organic polymer molecule obtained from the purified and dried sap of the "Isonandra percha" tree from the "Spatoceae" tree family in South Africa (19). The main components of gutta-percha cones are: 59-75% zinc oxide, 18-20% gutta-percha, and 1-17.2% metal sulfates (20).

There are three different forms of gutta-percha, two of which are crystalline form (α and β) and the other is amorphous form. Gutta-percha obtained from the sap of the isonandra percha tree is in α phase and is used in thermoplastic root canal filling methods. On the other hand, conventional gutta-percha cones are in β phase, they are less fragile than the α form and convert into α phase at about 47 °C. They melt at 53-59 °C and become amorphous (2). Phase changes of gutta-percha cause volumetric changes. During clinical applications, gutta-percha should be applied with pressure to avoid volume loss due to shrinkage during cooling (21).

Advantages of clinical use of gutta-percha cones can be listed as follows:

1. Can be easily compressed,

2. Has good dimensional stability,

3. Low toxicity,

4. Good radioopacity,

5. Acquires plastic characteristic when heated,

6. Can be removed by mechanical and chemical solvents when canals need to be emptied,

7. Shows biocompatibility with soft tissues (22, 23).

The disadvantages are listed below:

1. Insufficient hardness and lack of stability,

2. Length control is difficult in canals. Canal length control becomes difficult when there is no apical stop point (24, 25).

2.1.1. Root Canal Sealers

Root canal sealers have been shown to be effective in the success of root canal treatment (26). Root canal sealers are materials that enhance gutta-percha compatibility by filling voids and irregularities in the canal (27). When root canal sealer is not used during root canal treatment, voids are left between solid materials such as gutta-percha and root canal walls. Therefore, solid materials are used together with semi-solid materials in root canal treatment (28).

Intended purpose of root canal filling sealers can be listed as follows:

1. Provide adaptation of root canal filling material to the canal walls and fill the voids between the dentin walls and the filler material.
2. Make root canal filling easier by exerting a lubricant effect in the canal.
3. Root canal sealers contain antibacterial agents, therefore they show antibacterial effects after being placed in the root canal (29).

According to Grossman, the characteristics that need to be present an ideal root canal filling are as follows:

1. It should be adhesive when mixed and show good adhesion between the canal walls when hardened.
2. Should provide hermetic sealing.
3. Should be radiopaque so that it can be viewed in radiographs.
4. The powder part must contain fine particles so that it can be easily mixed with the liquid part.
5. Shrinkage should not occur during hardening.
6. Should not cause coloring in tooth structure.
7. Should be bacteriostatic or should at least prevent bacterial growth.
8. Should harden slowly.

9. Should not dissolve in tissue fluids.

10. Should be tissue-friendly and should not irritate peri radicular tissues.

11. When it has to be removed from the root canal, it should be soluble with solvents (27).

12. Should not produce an immune response in periapical tissues.

13. Should not show any carcinogenic or mutagenic effect.

A root canal sealer that meets all of these features is not available today (27).

Classification of Root Canal Sealers

Root canal filling sealers are materials that fill the region between the filling material and the dentin wall, irregularities within the canal, and lateral and accessory canals, and they have to be used in a successful canal treatment (27).

2.1.1.1. Zinc Oxide Eugenol Containing Canal Sealers

Root canal filling sealers containing zinc oxide eugenol are generally composed of two parts, powder and liquid. The powder is predominantly zinc oxide, with added radioactive materials and resin. The liquid is predominantly eugenol (30). After the hardening reaction of root canal filling sealers containing zinc oxide eugenol, free eugenol remains and results in irritation. According to tissue culture and implantation studies, free eugenol shows high toxic effect (31).

Barium sulphate is added to the contents instead of silver in order to provide radiopacity to prevent coloring on the tooth surfaces. Zinc oxide-eugenol-containing sealers have been modified over time by adding various chemicals to their contents. For example, paraformaldehyde has been added to increase antimicrobial activity. However, due to the toxicity of formaldehyde and the risk of affecting other tissues and organs through circulation, its use today is not recommended. In addition, germicides and iodoform have been added to sealers for antiseptic effect, and corticosteroids have been added for suppressing inflammatory reactions. Resin or Canadian Balsam has been added to increase dentin adhesion (30).

Root canal filling sealers containing zinc oxide eugenol are: Rickert sealer, Tubliseal, Grossman sealer, Wach sealer.

Paraformaldehyde-containing root canal filling sealers are: Endomethasone, N2 sealers, Riebler's sealer.

2.1.1.2. Calcium Hydroxide Containing Canal Sealers

Calcium hydroxide is often used as an intracanal medicament in endodontics. The first clinical use of calcium hydroxide as a root canal filling material was performed by Rhoner in 1940 (32). In the late 1970s, it began to be used as a canal sealer (33).

The reasons for the addition of calcium hydroxide to canal sealers are that it is effective in tissue repair, it can be resorbed when it goes out of the root canal, it contributes to hard tissue formation and it is antibacterial (34).

The calcium hydroxide in the canal sealer provides therapeutic effect. Calcium hydroxide can exert a therapeutic effect by being separated into Ca^{++} and OH^{-} ions. For this reason, calcium hydroxide-containing canal sealers need to be dissolved to form calcium hydroxide (35). As the canal sealer dissolves, the structural integrity of the sealer is disrupted and voids form. Especially when the sealer thickness is high, the possibility of dissolution is higher (36).

It has been shown that calcium hydroxide-containing canal sealers have weak dentin bonding (37) .

Calcium hydroxide-containing root canal filling sealers are: Apexit, Sealapex, Sealer26, Calciobiotic root canal sealer CRCS.

2.1.1.3. Glass Ionomer Containing Canal Sealers

Due to the dentin bonding properties of glass ionomers, they have been proposed to be used as canal sealers (38). Ketac-Endo (ESPE, Seefeld, Germany), the first glass ionomer-containing canal filling sealer that was released in 1991, made bonding possible between the canal wall and the filler material (39). It has been thought that chemical bonding of glass ionomer cements to dentin and enamel hydroxyapatite strengthens the roots (40).

There is no solvent that facilitates the removal of glass ionomer-based sealer from the root canal. For this reason, it is very difficult to remove these sealers from the canal (41).

Glass ionomer-containing sealers can cause leaks during the hardening reaction by becoming sensitive to moisture (42).

Glass ionomer-containing pats have minimal antibacterial activity (43). Their service life is insufficient. Due to their impractical clinical use, they are recommended to be used with single cone technique (42).

Glass ionomer-containing root canal filling sealers are: Ketac-Endo, Vitrabond, Endion, Activ GP Sealer.

2.1.1.4. Canal Sealers with Polymer Structure

They can be classified in four groups.

a) Polyketone Containing Sealers

Diaket (3M/ESPE Dental Prod, St. Paul, MN, USA) has been on the market since 1952. It consists of three parts as powder, liquid and melter.

Its adhesion to the dentin wall is strong. It is compatible with periapical tissues. Removing it from the canal is easy. Its service life is insufficient (44).

b) Epoxy Resin Containing Sealers

Epoxy resin-containing sealers have low solubility (45). Some shrinkage occurs after the volumetric expansion that occurs as the sealer hardens. In vivo and in vitro studies report that its covering ability is better than other sealers (46).

AH26 (Dentsply International, Maillefer) powder contains hexamethylene tetraamine, titanium dioxide, bismuth oxide and metallic silver. Its liquid contains bisphenol-glycidyl ether. Hexamethylene tetraamine and bisphenol diglycidylether enter a polymerization reaction and form formaldehyde. Formaldehyde formation continues until the sealer hardens and the effect gradually decreases (47). The amount of formaldehyde formed is thousands of times smaller than zinc oxide eugenol sealers containing paraformaldehyde (48). It can harden in humid environments. Its disadvantage is its coloring tendency and long hardening time (49).

AH Plus (De Trey, Dentsply, Konstanz, Germany) canal sealer does not form formaldehyde after polymerization. It is produced by eliminating the disadvantages of AH26 sealer such as coloring tendency and formaldehyde formation. However, the high radiopacity, low resolution and tissue compatibility characteristics of the AH26 sealer are preserved (50).

AH Plus shows less cytotoxicity than AH26. However, mutagenicity studies have reported that both sealers showed dose-dependent genotoxicity (51).

It has been shown that the dentin wall bonding and covering properties of AH Plus canal sealer are better than EndoREZ, Sealapex and Pulp Canal Sealer (52).

Epoxy resin-containing root canal filling sealers are: AH26, AH Plus, Sealer26, 2 Seal, TopSeal, EZ-Fill, Smartsealer.

c) Silicone Containing Sealers

Silicone-containing root canal sealers are polymethyl siloxane-based. They have the advantage of not showing polymerization shrinkage (53). Their weak antibacterial effects are their disadvantages (54).

Öztan et al. (2003) compared the cytotoxic effects of RoekoSeal and AH Plus, and reported that the two sealers were biocompatible and their cytotoxicity was minimal to none (55).

GuttaFlow is a modification of RoekoSeal sealer. The system that consists of gutta-percha particles and the sealer is applied cold. It is injected into the root canal with a cannula (56).

GuttaFlow shows a slight expansion (0.2%) after the hardening reaction. Successful results were obtained in leak studies conducted (57). However, there are studies that show that GuttaFlow causes apical leakage, and that canal fillings made by hot vertical condensation technique provide higher sealing (58).

Silicone-containing root canal filling sealers are: Lee Endofill, RoekoSeal, GuttaFlow.

d) Methacrylate Resin Containing Sealers

Resins that can bind to dentin by self-priming and acidification have previously been used in conservative dentistry. Recently, methacrylate resin containing root canal filling sealers have been started to be used in endodontics to obtain better apical and coronal coverage (59).

Epiphany canal sealer (Pentron Clinical Technologies, Wallingford, CT, USA) and Resilon (Resilon Research LLC, Madison, CT, USA) is a resin containing canal filling system. This system contains Epiphany primer which has a self-roughening property. 17% EDTA solution is used during shaping. After applying Epiphany primer and canal sealer, Resilon is placed in the canal. Thus, it is believed that dental tissues weakened during channel repair procedures are reinforced by the monoblock structure obtained (60). The second-generation product of this root canal filling system is Epiphany SE root canal sealer, which contains self-roughened dual-cure hydrophilic resin (61).

De-Deus et al. (2008) investigated Epiphany-Resilon and AH Plus-gutta-percha combinations in terms of apical coverage in the short and long term. While there was no difference between the two groups in the short term, Epiphany-Resilon group resulted in significantly more leakage in the 14-month period (62).

EndoREZ System (Ultradent Products, South Jordan, UT) is a system based on chemical bonding between polybutadiene diisocyanate-methacrylate resin coated gutta-percha and dual-cure root canal filling sealer with urethane dimethacrylate as an active agent (62). In a study where AH Plus and EndoREZ canal sealer is applied with lateral condensation technique, apical coverage of canal sealers and dentin adaptation were investigated. AH Plus was reported to have less leakage and higher dentin adaptation (63).

Methacrylate resin containing root canal sealers include: EndoRez, Epiphany, Fiberfill RCS, Real Seal, Simplifill SE, MetaSeal, Superbond RC sealer.

2.1.1.5. Bioceramic Containing Canal Sealers

Ceramics specially designed for the repair, restructuring, or replacement of organs that are damaged or lost their function are called bioceramic (64).

Bioceramic containing sealers have osteoinductive effects, they are biocompatible since they form hydroxyapatite form, they fill the root canal without any voids by expanding during hardening, and they have antimicrobial effect due to high pH. Therefore, bioceramic containing sealers have become an alternative material in clinical use (65).

While bioceramic-containing sealers do not dissolve in the root canal system, they dissolve when they move out of the canal from the apical direction (66).

Hydroxyapatite form is created by precipitation of calcium and hydroxide ions. Thus, a chemical bonding is formed between the canal filling and the dentin wall (17).

Loushino et al. (2011) compared the toxic effects of AH Plus and bioceramic-based sealer, and found that bioceramic-based sealer did not show toxicity and was a more biocompatible material (67).

De Siqueira Zuolo et al. (2016) investigated the removal of bioceramic-based sealer from canals, and reported that bioceramic-based sealers required more time than eugenol-containing sealers during removal of canal fillings (68).

Candeiro et al. (2016) compared antibacterial effects and cytotoxicity of AH Plus and bioceramic-based sealers. Bioceramic-based sealers showed similar antibacterial activity with AH Plus against *Enterococcus faecalis* and showed less cytotoxicity and genotoxicity than AH Plus (69).

Classification of bioceramic containing sealers:

a) Calcium-Silicate-Phosphate Containing Sealers

These sealers generally contain zirconium oxide, calcium silicate, calcium phosphate, calcium hydroxide, hydroxyapatite filler and hardener materials. The calcium silicate and hydroxyapatite in their content provide biocompatibility and bioactivity to canal sealer. Calcium-Silicate-Phosphate containing sealers are hydrophilic and harden by attracting moisture from the dentin tubules. Due to the small particle structure and fluidity, they can penetrate to the lateral canals and dentin tubules (70).

Calcium-Silicate-Phosphate-containing canal filling sealers include: BioSeal, Endosequence BC Sealer, iRoot SP, Smartsealer Bio.

b) Mineral Trioxide Aggregate (MTA) Containing Sealers

The first commercially available tricalcium silicate-containing sealer is MTA Fillapex (Angelus, Londrina, Brazil). MTA Fillapex consists of more salicylate residues than MTA (71). MTA Fillapex does not form calcium hydroxide during hydration and exhibits low calcium ion release during its dissolution (72).

MTA containing canal sealers are: MTA obtura, ProRoot Endo Sealer, DiaRoot Bio Aggregate, Endo CPM Sealer.

2.2. Root Canal Sealers Used In Our Study

2.2.1. AH Plus (De Trey, Dentsply, Konstanz, Germany)

AH Plus does not have the disadvantages of AH26 such as the coloring tendency and the formation of formaldehyde. It is also advantageous that formaldehyde is not formed after polymerization. In addition, high radiopacity, low resolution and tissue compatibility features of AH26 sealer are preserved (50).

Covering capability was compared in oval-shaped root canals filled with Guta-percha and AH plus canal sealer using lateral condensation, System B and Thermafil techniques. According to bacterial leakage test results, there was no significant difference between the techniques in terms of covering ability (73).

Oliveira et al. (2016) compared the binding strengths of AH Plus, iRoot SP and MTA Fillapex PAW using the push-out test. AH Plus produced higher bonding values than iRoot SP and MTA Fillapex. No difference was found between two bioceramic containing sealers (74).

Gandolfi et al. (2013) performed void space volume comparisons in root canals they filled with AH Plus and MTA Flow canal sealers using the Thermafil technique. When assessing void space, they separated the root into three sections as apical, middle, and coronal thirds. In root apical third, MTA Flow resulted in less voids than AH Plus. Similar void spaces were observed in the middle and coronal thirds of the root. When the root was divided into three sections and evaluated, it was found that there was less void space in the canal filling in the apical third of the tooth (75).

Graunaite et al. (2018) compared the effects of bioceramic and resin containing root canal sealers on the incidence and severity of postoperative pain in patients with asymptomatic apical periodontitis. AH Plus and Total Fill had a similar effect on the incidence and severity of postoperative pain in asymptomatic apical periodontitis teeth without material extrusion outside the apex (76)

Table 1. Contents of AH Plus sealer (77)

Contents of AH Plus Sealer	
Sealer A (epoxy sealer)	Sealer B (amine sealer)
Diglycidyl-bisphenol-A-ether, Calcium tungstate, Zirconium oxide, Aerosol, Iron oxide, Pigment	1- Adamantane amine, NN-1,9-dibenzyl-5-oksanonandiamine-1,9 TCD-diamine, Calcium tungstate, Zirconium oxide, Silicone oil

2.2.2. MM seal (Micro Mega, Besancon, USA)

MM seal is an epoxy resin-based root canal sealer packed with double syringe. According to the manufacturer's claim, it has superior physical and chemical properties and allows the root canal to be filled in a sealed manner. Polineni et al. (2016) assessed the adaptation qualities of Endosequence BC Sealer, MM seal and MTA Fillapex canal sealers to the dentin wall using scanning electron microscopy. Marginal spaces between dentin and canal sealer were examined by scanning electron microscopy in the sections taken from the apical and coronal thirds of the root canal filled with single cone technique. Lower adaptation to dentin was detected in the apical third of canals than in the coronal third. Epoxy resin containing MM seal sealer showed better marginal adaptation than other sealers (78).

Madhuri et al. (2016) compared the dentin bonding strength of MM seal, Endosequence BC Sealer, MTA Fillapex and Hybrid Root Seal canal sealers with the push-out bonding strength tests performed on extracted teeth. 2 mm sections obtained from teeth filled with single cone technique were used. Endosequence BC Sealer group showed higher bonding to dentin than other groups. The group with the second highest bonding was the MM seal group. MTA Fillapex group showed the least bonding. This result was attributed to the fact that the Endosequence BC Sealer forms the hydroxyapatite form as a result of dentin bonding and has a low contact angle that allows it to spread easily (79).

Table 2. Contents of MM Seal sealer (80)

Contents of MM Seal sealer	
Base	Catalyzer
Epoxy oligomer resin Ethylene glycol salicylate Calcium phosphate Bismuth sub carbonate Zirconium oxide	Poly aminobenzoate Triethanolanoine Calcium phosphate Bismuth subcarbonate Zirconium oxide Calcium oxide

2.2.3. Endosequence BC Sealer (Brasseler, Savannah, Georgia, USA)

Endosequence BC Sealer is hardened by absorbing the water in the dentin tubules thanks to its hydrophilic nature. It is insoluble in water and radiopaque (81). Its operation time is 4 hours. The material is premixed and placed in a syringe. Calcium ion release is more than AH Plus canal sealer. Compared with biodentin and white MTA, it releases less calcium (75). It has been shown to be biocompatible (82).

Shokouhinejad et al. (2013) compared the push-out bond strengths of AH Plus and Endosequence BC Sealer pats in the presence and absence of a smear layer. There was no statistically significant difference in bonding strength between groups filled with AH Plus and Endosequence BC Sealer. The presence or absence of the smear layer did not have a significant effect on the bonding strength of the canal sealer. The authors attributed these findings to the fact that bioceramic containing sealer and white MTA contained a similar compound (83).

Çelikten et al. (2016) evaluated the presence of voids in canal fillings using micro-CT in extracted teeth filled with AH Plus, Endosequence BC Sealer, Smartsealer bio and ActiV GP canal sealers. Void spaces were found in canal fillings made with all root canal sealers. Bioceramic sealers (Endosequence BC Sealer, Smartsealer bio) produced similar void spaces with other groups. The least space was seen in the apical part of the canals (84).

Zoufan et al. (2011) compared Endosequence BC Sealer and GuttaFlow canal patties with AH Plus and Tubli-Seal canal sealers in terms of cytotoxicity. Endosequence BC Sealer and GuttaFlow showed less cytotoxicity than AH Plus and Tubli-Seal (85).

Huang et al. (2018) examined the sealing properties of AH Plus and Endosequence BC Sealer canal sealers using scanning electron microscope (SEM) and Micro-CT in teeth filled with single cone technique. There was no difference between AH Plus and Endosequence BC Sealer in terms of dentin tubule penetration and sealing properties. Better coverage was obtained in the coronal and middle thirds of the root than the apical with both sealers (86).

El Sayed et al. (2018) compared the apical coverage properties of two different single cone filling materials using AH Plus, MTA Fillapex and EndoSequence BC Sealer sealers. Groups 1, 2 and 3 were filled using single cone technique with gutta-percha and AH Plus, MTA Fillapex, and EndoSequence BC Sealer, respectively. Groups 4, 5 and 6 were filled using single cone technique with CPoint and AH Plus, MTA Fillapex, and EndoSequence BC Sealer, respectively. Group 7 was filled with gutta-percha and AH Plus sealer using lateral condensation technique. The dye penetration technique was used to measure apical leakage. Although the least among of leakage was obtained in the CPoint/EndoSequence BC Sealer group, there was no significant difference between the groups (87).

Table 3. Contents of Endosequence BC Sealer sealer (77)

Contents of Endosequence BC Sealer
Zirconium oxide
Calcium silicate
Calcium phosphate
Calcium hydroxide
Thickening agents

2.2.4. BioRoot RCS (Septodont, Saint-Maur-des Fosses, France)

BioRoot RCS is a novel endodontic canal sealer that is similar to Biodentine and contains tricalcium silicate. It has good fluidity and a smooth texture to provide adequate adhesion in the root canal (88).

BioRoot RCS exhibited twice as much calcium ion release as EndoSequence BC Sealer. Calcium ion release increases the pH of the medium. It is thought to have a high antimicrobial effect due to this alkaline environment. It also forms a calcium phosphate phase when it comes into contact with body fluids (89).

Its operation time is at least 10 minutes and its hardening time is at most 4 hours. It consists of two parts, powder and liquid (90).

BioRoot RCS canal sealer is recommended to be used with lateral condensation or single cone filling techniques. This is because the physical properties of the sealer change due to heat released during hot vertical condensation (91). Its fluidity decreases due to heat, its operation time is shortened and its film thickness increases (92).

Colombo et al. (2018) compared BioRoot RCS channel sealer with AH Plus channel sealer and found that they had similar cytotoxicity and antibacterial properties, but the solubility property of BioRoot RCS sealer was lower than ISO 6876 requirements (93).

In a study conducted by micro-computed tomography (micro-CT) analysis, the channels were filled according to the lateral condensation method with BioRoot RCS and AH Plus canal sealer. More voids were observed in the canals filled with BioRootRCS (94).

Eldeniz et al. (2016) compared BioRoot RCS and traditional canal sealers in terms of toxicity. BioRoot RCS showed less cytotoxicity and genotoxicity than AH Plus, Acroseal, EndoREZ, RealSeal SE, Hybrid Root Seal, iRoot SP, and MTA Fillapex (95).

Table 4. Contents of BioRoot RCS sealer (16)

Contents of BioRoot RCS	
Powder	Liquid
Tricalcium silicate Zirconium oxide Povidone	Aqueous calcium chloride solution Polycarboxylate

2.3. Physical and Chemical Properties of Root Canal Sealers

Physical properties of canal sealers are defined during mixing and hardening. Physical and chemical properties of canal sealers can be defined based on adhesion properties, fluidity, film thicknesses, solubility and absorption criteria (96).

Fluidity is a feature that allows the irregularities in the canal walls to be filled after the canal is mechanically shaped. It is difficult to fill the cavities on the walls if the sealer is less fluid. If it is too fluid, there is a possibility of overflowing from the apical foramen. An ideal fluidity value for canal sealers has not been determined (44). Although the ideal fluidity properties are not yet specified, canal sealers with these features have good dentin bonding, thereby resulting in a well-adapted root canal filling (97).

Film thickness is the minimal thickness that the root canal filling sealer can exhibit under a specific load. As the film thickness of the canal filler decreases, its ability to soak will increase. It can be said that the film thickness will increase the amount of gutta-percha cones in the canal filling, thus reducing apical leakage. However, no link between leakage and film thickness has been identified so far (98).

Solubility is defined as the ability of a substance to be separated into its molecules in a liquid. In a root canal sealer, dissolution can occur through superficial erosion, from cracks in the structure or from melting in the main body. This disrupts the quality of the hermetic covering provided in the canal (44).

During absorption, the liquid penetrates the solid material by diffusion. The more porous the material is, the greater the amount of absorbed liquid will be and the volumetric changes will occur in the solid material (44).

2.3.1. Adhesion

Use of root canal sealer and gutta-percha in root canal fillings has been accepted as the gold standard. It has been reported that apical and coronal leakage that may occur in the root canal may be reduced as root canal sealer shows adhesion to both the dentin and gutta percha (13).

Adhesion can be described as the force of attraction between the molecules at the interface of different materials. The bonded material is called the adhesive and the surface on which adhesion occurs is called the adherent (14).

A chemical or mechanical mechanism is required for bonding to occur. For mechanical bonding, the adhesive penetrates and is then bonded to the rough surface of the adherent. For chemical bonding, the adhesive is attached to the adherent at the molecular and atomic level (99).

Endodontic bonding is defined as the resistance of the root canal filling against dissociation from root canal dentin. Endodontic bonding is important because of static and dynamic effects. The static effect is the removal of the cavities that will cause fluid passage between the root canal filling and the root canal dentin (12).

Apical third of the root contains less dentin tubules than the coronal third (100). However, in some studies it has been reported that root canal region has no effect on the dentine bonding strength of canal sealers (101, 102), whereas some studies have reported low bonding strength in the apical region (103), and one study has reported high bonding strength in the apical region (104). The bonding strength to root canal dentin may be associated with the dentin area rather than the amount of dentin tubules (101).

Sodium hypochlorite (NaOCl), which is used in the irrigation of root canals, reduces dentin bonding strength by inhibiting the polymerization of resin-containing canal filling sealers (13).

Smear layer is the layer that covers the surface of the dentin after the root canals are mechanically shaped. Studies evaluating the effect of the smear layer on dentin bonding of canal sealers argue that removal of the smear layer results in better adhesion of the sealer to dentin tubules (11, 105).

Bond strength tests are used to assess adhesion between canal filling sealers and root canal dentin, but no bonding test has so far been universally accepted. According to the orientation of the force that is involved in assessing the bonding of root canal fillers to the dentin, Shear bond strength, Pull-out, Microtensile and Push-out tests are being used (11).

In the shear test, the force is applied parallel to the substrate and the interface that adhesive is bonded to. The difficulty of positioning the shear load device close to the adhesive-bound interface is the most important problem of the shear test (90).

In the pull-out test, the test surface prepared in special molds is placed in the table of the test device and fixed in the appropriate position, and bonding strength is measured by pulling the test material by the force-applying tip of the device at a constant speed in the reverse direction (91). Small differences in stress distribution during loading have significant effects on the results. For this reason, pull-out test is highly sensitive (92).

The microtensile method uses small sized samples and allows for uniform stress distribution at the bonding interface (93). The application of the microtensile method was not considered appropriate in evaluating root canal sealers with low bonding strength (14).

Push-out test has been used in dentistry since 1970 (94). Studies evaluating bonding to root canal dentin have been carried out since 1996 (95). Push-out technique is carried out on sections obtained from canal-filled root canals. With the help of a pusher tip, the root canal filler is pushed through the root canal and the maximum force allowing the canal filler to break gives the bond strength value. The applied force is perpendicular to the dentine tubules, and parallel to the bonding surface (96). It is stated that push-out test is more reliable than other tests, many premature failures occur during preparation of samples in the microtensile test and that the data are distributed over a wide range. In addition, the force is parallel to the bonding surface and better reflects the clinical state (86).

2.3.1.1. Studies Evaluating Adhesion of Root Canal Filling Sealers

Oliveira et al. (2016) examined the push-out bonding strength of MTA Fillapex (Angelus, Londrina, Brazil) and IRoot SP (Innovative BioCeramix Inc. Vancouver, Canada), which has the same content as and Endosequence BC Sealer, to root canal dentin walls. AH Plus and MTA (Angelus, Londrina, Brazil) were used as the control group. The root channels of the extracted teeth were expanded in the middle thirds using Gates Glidden drills. Then, channel sealers were sent with the aid of lentulo to the canals and control radiographs were taken. 1 mm sections were obtained from each sample and bond strengths were measured by push-out test method. MTA Fillapex and iRoot SP showed lower bonding than the other groups. No difference was found between the two channel sealers containing calcium silicate (74). Nagaş et al. (2012) concluded that AH Plus sealer showed lower bonding to the dentin wall than iRoot SP. In the study, samples were shaped with ProTaper rotary instruments (Dentsply Maillefer, Ballaigues, Switzerland) and canal fillings were made with System B (SybronEndo Corp., Orange, CA) and Obtura (Obtura Spartan, Fenton, MO) systems (106). This difference between the studies was mainly attributed to differences between the experimental designs (74).

Madhuri et al. (2016) compared the bonding of MM seal, Endosequence BC Sealer, MTA Fillapex and Hybrid Root Seal canal sealers to root dentin with the push-out bond strength test. 2 mm sections were obtained from extracted teeth filled with single cone technique. Endosequence BC Sealer group showed higher bonding to dentin than other groups. The group with the second highest bonding was the MM seal group. The MTA Fillapex group showed the least bonding. This result was attributed to the fact that Endosequence BC Sealer creates a hydroxyapatite form after dentin bonding and has a low contact angle that allows it to spread easily (79).

Yap et al. (2017) investigated the bonding of AH Plus with epoxy resin, TotalFill BC (FKG Dentaire, La Chaux-de-Fonds, Switzerland) with bioceramics and

EndoREZ (Ultradent, South Jordan, UT, USA) with methacrylate resin to root dentin using push-out tests. 2 mm sections were obtained from extracted teeth that were filled with canal sealers and angled cones using a single cone technique. The sections in each group were divided into two groups and subjected to push-out test after 2 weeks and 3 months. AH Plus and TotalFill BC sealers showed similar dentin-bonding properties. Furthermore, their bonding to dentine increased over time. EndoREZ sealer was reported to exhibit significantly lower bond strength values. The high fluidity of the TotalFill BC sealer enabled it to show better adhesion to the dentin tubules. As a result, it was reported that dentin bond strength values of canal sealers were related to the time passed after canal filling and the contents of the canal sealer (107).

DeLong et al. (2015) compared the dentin push-out bonding strengths of EndoSequence BC sealer and MTA Plus canal sealers using single-cone and continuous-heat filling techniques. Samples were sectioned at 1 mm thickness and bonding strengths were examined by applying a standard pushing force. The use of single cone technique resulted in higher bonding. EndoSequence BC sealer applied with single-cone technique showed the most significant bonding values. Continuous heat filling technique reduced the dentin bonding strength of these canal sealers (108).

In a study evaluating the dentin bonding strength of iRoot SP, AH plus and Apexit plus canal sealers in the presence or absence of a smear layer, the roots were divided into three groups according to the type of canal sealer used. Group A: Apexit plus + gutta-percha, Group B: AH Plus + gutta-percha, Group C: iRoot SP + gutta-percha. The groups were then divided into two subgroups according to the final wash solutions. Groups (A1, B1, and C1) were washed with 5 ml of 5.25% NaOCl for 1 minute whereas (A2, B2, and C2) were washed with 5 ml of 17% EDTA for 1 minute. All groups were rinsed with distilled water and then filled with cold lateral condensation technique. The results showed that the bond strengths of iRoot SP and AH Plus were significantly higher than Apexit plus, but there was no significant difference between bond strengths of iRoot SP and AH Plus. Bond strengths were found to be higher in the middle and apical thirds of the root compared to the coronal third. The presence or absence of the smear layer did have a significant effect on the dentin bonding strength of the filling materials (109).

Sagsen et al. (2011) were unable to detect a significant difference between the MTA Fillapex, iRoot SP, and AH Plus canal sealers when bond strength was tested in sections taken from the coronal third of root canals. However, iRoot SP and AH Plus showed better bonding than MTA Fillapex in the apical and middle thirds of root canals (110).

Elbatouty et al. (2015) compared the dentin bonding strengths of a bioceramic-containing canal sealer (EndoSequence BC Sealer), zinc oxide-eugenol-containing canal sealer (Kerr EWT) and AH Plus sealer. 2 mm horizontal sections were obtained from extracted teeth divided into three groups. Push-out bond strength was measured using a universal testing machine on days 7, 14, and 30 after canal filling. The highest bonding strength was found in samples filled with EndoSequence BC Sealer sealer at 1 and 4 weeks after canal filling (111).

Pawar et al. (2016) compared the push-out bond strengths of oval root canals shaped by Self Adjusting File (SAF) or WaveOne (WO) ResiProc systems after being filled with CPoint and Endosequence BC sealer or gutta-percha and AH Plus. The highest value was recorded in the root canals shaped by the SAF System and filled with C-Point and Endosequence BC sealer, while the lowest value was recorded in the canals shaped by WaveOne and filled with gutta-percha and AH Plus. As a result, the canal tool and channel filling material used in oval canals significantly affected the bonding values of the canal fillings (112).

Alfredo et al. (2008) conducted an in vitro study on the bonding strengths of Epiphany and AH Plus canal filling sealers, using a 980 nm diode laser beam applied to the 4-mm thick dentin blocks prepared. The blocks were then filled with AH Plus or Epiphany to create two different experimental groups. All the samples were subjected to push-out bonding test and the obtained data were evaluated statistically. The study concluded that the AH Plus canal filling sealer showed significantly higher bond strength to dentin tissue than Epiphany and that 980 nm diode laser application increased the bonding strength of AH Plus (113).

2.4. Classification of Root Canal Filling Techniques

Currently used root canal filling techniques can be classified as follows:

1. Single cone technique
2. Lateral condensation of cold gutta-percha
3. Chemical softening of cold gutta-percha
4. Continuous heat filling technique
5. Lateral/vertical condensation of warm gutta-percha

6. Thermomechanical condensation of gutta-percha
7. Thermoplastic injection techniques
8. Carrier-based gutta-percha systems (114).

2.4.1. Single Cone Technique

After shaping the root canals with rotary device systems, a gutta-percha cone with the correct working length that is dimensionally and angularly compatible with the last used file of the system is selected and applied (115).

In the root canals filled with single cone technique, the volume of the channel sealer is greater. Over time, voids are formed in the channel fill as the sealer dissolves. Therefore, the quality of the canal fill decreases (46). The advantage of this technique is that it is easy to apply and can be applied in a short time (116).

2.4.2. Lateral Condensation of Cold Gutta-Percha

Cold lateral condensation technique is the most commonly used canal filling technique for filling root canals. If the canals are not highly curved, if they do not show anatomical irregularity, and if the roots are not open-apexed, cold lateral condensation technique can be easily used in all tooth groups (117).

In the lateral condensation technique, the main cone is selected first. With the main cone selected, a resistance called 'tug back' should be felt in the apical part. After the root canals are disinfected with irrigation solutions, they are dried with paper cones. Canal sealer is applied to the canal and the main cone is covered with sealer and inserted into the canal. Spreader that is compatible to the canal size is then applied until 2 mm to the working length. Auxiliary cone covered with sealer is then placed in the gap created by the spreader. By repeating this process, the space between the dentin wall and the main cone is filled with auxiliary cones (27).

Advantages of lateral condensation technique include maintaining canal length control, good dimensional stability, and easy application of retreatment and post-void preparation (118).

When lateral condensation technique is applied on inadequately shaped root canals, the spreader cannot provide adequate compression and voids are formed. This causes excessive sealer thickness (119). Applying excessive force on the spreader during lateral condensation can cause root fractures (120).

2.4.3. Chemical Softening of Cold Gutta-Percha

It is a technique in which gutta-percha is used after being dissolved with solvents such as chloroform, halotene and eucalyptol. The use of chemical solvents increases the likelihood of flooded channel filling and reaction in periapical tissues (121).

2.4.4. Continuous Heat Filling Technique

System-B heat source monitors the heat at the tip of the heat carrier and the heat is applied for a certain period. Heat carrier heats gutta-percha and also condenses it in the vertical direction (27).

The disadvantages of the technique are the side effects caused in periodontal tissues due to heat and the large diameter of the heat carrier tip. A temperature increase of 10 °C causes irritation in periodontal tissues (122).

2.4.5. Lateral/Vertical Condensation of Warm Gutta-Percha

Vertical condensation method proposed by Schilder in 1967 can be summarized as the selection of suitable pluggers after expansion of the root canals, the adjustment of the main cone and being inserted into channel with some sealer, the softening of the gutta-percha with the heating tip in a controlled manner and the compression of warm gutta percha in the vertical direction with plugger (44).

2.4.6. Thermomechanical Condensation of Gutta-Percha

The technique developed by McSpadden uses the McSpadden compactor that looks like a reversed Hedström file. The tool produces the necessary heat by creating friction and softens the gutta-percha so that the root canal system is filled with the filling material (115).

The advantages of thermomechanical condensation technique are that the filling time of the canal is short, and the technique allows the filling material to reach root canal irregularities and lateral canals. The disadvantages are fractures that occur at compactor tips and flooded canal filling (115).

2.4.7. Thermoplastic Injection Techniques

This is a technique in which canals can be filled by injection of gutta-percha heated outside the canal into the canal (123). Due to the fluid structure of heated gutta-percha, irregular structures of the root canal, side channels and apical delta can be filled. However, condensation must be provided using a plugger to prevent shrinkage that occurs as heated gutta-percha cools down (124).

During root canal filling with thermoplastic injection techniques, apical stenosis should be preserved during canal shaping in order to prevent gutta-percha from going out of the canal. Difficulty in dimensional control is one of the difficulties of the system. Hybrid technique can be used to avoid flooded or insufficient canal fillings. The apical 4-5 mm section of the root canal can be filled with lateral condensation or vertical condensation technique, compressed with a heated plugger, and then coronal section can be filled with thermoplastic injection technique (125).

Calamus (Dentsply Tulsa Dental Specialties) is a thermoplastic device used with a cartridge system of 20 and 23-gauge needles. Pluggers can also be used with the system. Ultrafil 3D (Coltene/Whaledent) and Elements (Sybron Endo) are also instruments used to apply heated gutta-percha injection technique (125).

2.4.8. Carrier-Based Gutta-Percha Systems

Carrier-based gutta-percha systems were first introduced in 1978 by Johnson, where a stainless steel canal file was covered with alpha-phase gutta-percha and used as canal filling material after being heated (126).

Thermafil (Dentsply Tulsa Dental Specialties) is obtained by coating α-phase gutta-percha on the stainless steel, titanium and plastic carrier part. The Thermafil technique is advantageous because of its ease of application and its ability to fill the canal three dimensionally thanks to the fluidity of gutta-percha. However, flooded fillings, gutta-percha sliding off the carrier and the apical section retaining only the carrier during the filling process, the difficulties encountered during retreatment and post-preparation are the disadvantages of the technique (49).

Profile GT Obturators (Dentsply Tulsa Dental Specialties, Tulsa, OK) and GT systems use this technique (49).

2.5. Evaluation of Root Canal Filling Material Quality

The quality of root canal filling can be assessed by the percentage of voids in the canal fill. After irrigation and shaping of the canals, the remaining bacteria are trapped in the canal filling. The presence of cavities in the canal fill may lead to leakage, creating a path for bacteria remaining in the canal, and canal treatment may ultimately fail (127).

Microleakage in root canals is defined as the passage of bacteria and chemical substances between root canal filling material and dentin tissue (128). Microleakage resulting from the presence of voids between root canal filling material and dentin tissue may occur due to inadequate bonding of the filling material to the canal wall (129).

It has been reported that polymerisation shrinkage of as low as 1% in root canal sealers after root canal filling is sufficiently large for the penetration of bacteria and harmful by-products (130).

In conclusion, it is clinically important to identify voids in the canal filling, and canal filling techniques and canal sealers used are important determinants of total void space (131).

There are many methods used to evaluate the quality of root canal fillings *in vitro*. These are radiography technique, dye penetration studies, fluid filtration method, bacterial studies, scanning electron microscopy studies and micro-CT technique (10, 53).

Radiographs are not ideal because they produce a two-dimensional image and it is difficult to identify voids (132).

In dye penetration studies, sample preparation is done by breaking the root longitudinally, pellucidation or taking perpendicular sections to the long axis of the root. It has been reported that the void space between the root canal dentin and root canal filling is detected by the penetration depth of the paint (133). The disadvantage of the method is that measurements cannot be repeated due to fragmentation of samples (8). This technique does not fully reflect the relationship between root canals and periradicular tissues according to clinical conditions (134).

In the liquid filtration method, the amount of microleakage in root canal fillings is measured without damaging the root samples. Repeated measurements over time are possible. Microleakage is measured by measuring the pressure lost in the static system by applying compressed air through the root canal to the samples (36). The disadvantage is that the measurements are subjective (135).

It is important to work sterilely to avoid erroneous results in bacterial microleakage studies. It is more suitable for clinical conditions than dye penetration studies (136). However, which of the bacterial species to be used in the study will yield reliable results is still under debate (137).

Scanning electron microscopy analysis is based on measuring the distance between two bonding surfaces. The disadvantage is that during cross-sectioning of the specimens, there may be material loss in the sections and the channel fill material may be displaced (138).

The use of micro-CT technique is recommended to avoid the negative features of other techniques. It is stated that the micro-CT technique does not exhibit the disadvantages of other techniques used in the evaluation of root canal fillings because it does not damage the samples. It is possible to re-scan the specimens so that the changes occurring in the canal fill can be identified (8).

2.5.1. Micro Computed Tomography (Micro-CT)

In 1895, Roentgen identified x-rays, and developed a technology that enabled non-invasive visualization of interior regions of the body (139). This was an important development in medicine. In traditional radiography, x-rays pass through the object and a two-dimensional image is obtained by the transmitted energy. It is possible to obtain three-dimensional structure information by using computer algorithms after the sample is imaged repeatedly from different directions. This is called tomographic reconstruction (140).

By means of three-dimensional reconstruction processes, the sections taken from the desired sample can be reconstructed in the digital environment by combining them with various programs in the computer environment. In endodontic studies, three-dimensional reconstruction began to be used in the 1990s (141).

Micro-computed tomography (micro-CT) systems were developed at the beginning of 1980's. While clinical computed tomography systems produce images of 1 mm^3 voxels, micro-computed tomography yields better spatial resolution by producing voxels at a range of 5-50 µm (142). With Micro-CT, clear images can be obtained from even the smallest details; images can be created from details smaller than 1 µm. In Micro-CT, while the x-ray source and detector are generally stationary, the object is rotated around its axis. This reduces vibration and increases resolution. In a clinical computerized tomography device, the x-ray source and detector are rotated around the patient. This results in mechanical vibration (140).

The micro-CT technique has many advantages. The results are reproducible and can be compared with histological studies (143). The process can be performed without disrupting the samples. Thus, the root canal system can be examined without causing any damage (144).

Studies using micro-CT in dental research include: analysis of root canal morphology, assessment of root canal preparation, irrigation and debris accumulation, tissue engineering, root tip surgery, evaluation of root canal fillings, anthropological studies, evaluation of implants and bones around implants, and mineral concentrations of teeth (140).

In endodontic studies, micro-CT is mostly used for root canal anatomy and root canal preparation, followed by evaluation of root canal morphology (8). There are also studies where quality of root canal filling is assessed with micro-CT (84, 94, 145, 146).

2.5.2. Studies Evaluating the Quality of Root Canal Filling Materials

Hegde and Arora (2015) studied the apical coverage of root canal filling sealers with glycose penetration tests. In their study, they used AH plus sealer with lateral condensation technique and Endosequence BC Sealer and RealSeal SE sealers with single cone technique. As a result of the study, it was stated that the Endosequence BC Sealer sealer provided better apical coverage (147).

Pawar et al. (2014) investigated leakage using dye penetration method on root canals filled with Endosequence BC Sealer, AH Plus and Epiphany root canal filling sealers and continuous heat technique. Horizontal sections were taken from the teeth at 2, 4 and 6 mm from the apical while dye penetration method was used. Obtained sections were examined with steromicroscope. It was found that various grades of leakage was present in all experimental groups, while Endosequence BC Sealer and Epiphany canal sealers provided significantly better coverage (148).

Gandhi et al. (2017) used the bacterial leakage model to compare the coverage of root canal filling materials. As a result of the statistical analysis, it was reported that the iRoot SP canal sealer was significantly less leaky than the ProRoot MTA material. Researchers reported that complete coverage could not be achieved in any of the groups studied (149).

In a study investigating the dentin tubule penetration and canal filling quality of iRoot SP (Innovative BioCeramix Inc, Vancover, British Columbia, Canada), which has the same content as Endosequence BC Sealer and is a ceramic-based canal sealers, 40 lower incisors were used. Teeth were filled with iRoot SP and AH Plus sealer with single cone and hot vertical condensation techniques. Horizontal sections were taken from the teeth at apical 2, 4 and 6 mm distances. Obtained sections were examined with a stereo microscope and a laser scanning confocal microscope and the percentages of void spaces were calculated. It was found that the filling techniques used, and canal sealers did not have a statistically significant effect on void formation. In sections taken from 2 mm of the apical, the penetration of the iRoot SP sealer into the dentin tubules was significantly higher than AH Plus in both techniques. It was reported that IRoot SP sealer had better dentin tubule penetration than AH plus, and achieved a similar fill quality (150).

Çelikten et al. (2016) evaluated the presence of voids in canal fillings via micro-CT in extracted teeth filled with AH Plus, Endosequence BC Sealer, Smartsealer bio and ActiV GP canal sealers using single cone technique. Void spaces were found in canal fillings made with all root canal sealers. Bioceramic sealers (Endosequence BC Sealer, Smartsealer bio) produced similar void spaces with other groups. The least void space was seen in the apical part of canals (84).

Viapiana et al. (2016) performed a micro-CT analysis of canals filled according to the lateral condensation method with BioRoot RCS and AH Plus canal sealer. More voids were observed in the canals filled with BioRoot RCS (94).

Keleş et al. (2014) compared the filling materials and void space percentages in canal fillings made by lateral condensation and hot vertical condensation techniques. Single-rooted upper molar teeth with oval shaped canals were used in the study. All samples were scanned with micro-CT at 12.5 µm isotropic resolution. As a result, there were significantly more gutta-percha percentage and less void percentage in the canals filled with hot vertical condensation technique. Regardless of canal filling technique, distribution of canal sealer and void spaces is unclear (145).

Wolf et al. (2014) studied the presence of voids in canals filled with hot vertical condensation technique using calcium hydroxide-containing Seealapex (Kerr Sybron, USA), resin-containing 2Seal (VDW, Germany) and silicone-containing RoekoSeal.

They used micro-CT and evaluated the samples three dimensionally. Silicone-containing RoekoSeal canal sealer showed significantly less void space than the other groups. In the apical part of the root, void space was larger than the coronal and middle parts (146).

In a study investigating the effect of different irrigation solutions on the sealing properties of Endosequence BC Sealer, three groups were formed according to the type of the final irrigation solution used. 17% EDTA, MTAD and 2% chlorhexidine groups were further divided into two subgroups as AH Plus and Endosequence BC Sealer according to the canal sealer used. Root canals were filled with single cone technique and kept in 2% methylene blue solution for 48 hours after 1 week of incubation. Dye penetration was measured with stereomicroscope. It was found that the group with the lowest leakage was Endosequence BC Sealer and chlorhexidine group. In conclusion, using bioceramic-containing root canal filling material with chlorhexidine solution increases apical coverage (151).

3. MATERIALS AND METHODS

3.1. Sample Preparation

In our study, 64 single-root human mandibular premolar teeth with straight canals and no fractures or cracks in their crown and roots, newly extracted due to periodontal, orthodontic and prosthetic reasons were used. Care was taken to ensure that the root lengths of the teeth included in the study were similar, that the apical formations of the roots were complete, and that there were no calcifications in the canal. Digital radiographs were taken from the teeth in mesio-distal and bucco-lingual directions (Figure 1), and those who met the necessary conditions were included in the study. Teeth with multiple canals were not included in the study and replaced with new ones.

Tissue residues on root surfaces of teeth were removed with the aid of periodontal curette. Teeth were kept in normal saline until used in the study.

Crowns of all sample teeth were removed at the enamel-cement border with a cross-section device (Metkon, Microcut PrecisionCutter, Bursa, Turkey) running under water cooling so that root length would be 15 mm (Figure 2).

Figure 1. Digital radiographs taken from the teeth in mesio-distal and bucco-lingual directions

Figure 2. Crowns of all sample teeth were removed at the enamel-cement border

3.1.1. Root Canal Shaping

The presence or absence of obstruction in the apical foramen of the roots was checked with a K-type file No. 10 (Dentsply Maillefer, Ballaigues, Switzerland).

The working lengths of the root canals were determined to be 14 mm, 1 mm shorter from the apical. In accordance with manufacturer’s instructions, all canals were shaped into SX, S1, S2, F1, F2, F3 and F4 by X-SMART Plus endo motor (Dentsply, Fleece) (Figure 4) using Protaper Universal (Dentsply, Maillefer, Ballaigues, Switzerland) rotary files (Figure 3). The work length was maintained by using a "patency file" before every file change. After each file irrigation was performed by 2 ml of 5% sodium hypochlorite solution (Wizard, Guide Chemical, Turkey). After shaping was complete, the canals were washed with 5 ml 17% EDTA (Wizard Guide Chemical, Turkey) and 5 ml of 5% sodium hypochlorite (Wizard Guide Chemical, Turkey) for 1 min to remove the smear layer in the root canal and dried. As the final wash, 5 ml of distilled water was used to remove the wash solutions. The canals were dried with paper points.

Figure 3. Protaper Universal (Dentsply, Maillefer, Ballaigues, Switzerland) rotary files

Figure 4. X-SMART Plus endo motor (Dentsply, Maillefer)

Root diameters in the kole region were measured in the buccolingual direction (Figure 5). Samples were divided into four groups including 16 teeth in a randomized stratified manner (Figure 6).

1) AH plus (Dentsply De Trey GmbH, Germany)

2) MM seal (Micro Mega, Besancon, USA)

3) Endosequence BC sealer (Brasseler, Savannah, USA)

4) BioRoot RCS (Septodont, Saint Maur Des Fosses, France)

Figure 5. Measuring the diameters of the roots in the buccolingual direction

Figure 6. Diveded of roots into groups of 16

Table 5. Root canal sealer contents and manufacturer firms

Canal Sealer	**Content**	**Manufacturer firm**
AH plus	Pat A (epoxi) : Diglycidyl ether-bisphenol-A, Calcium Tungstate, Zirconium Oxide, Aerosol, Iron Oxide, Pigment Pat B (amine) : 1- Adamantane amine, NN-dibenzyl-5-oxanonanediamine 1,9, TCD-Diamine, Calcium tungstate, Zirconium oxide, Silicone oil	Dentsply De Trey GmbH, Germany
MM seal	Base: Epoxy oligomer resin, Ethylene glycol salicylate, Calcium phosphate, Bismuth subcarbonate, Zirconium oxide Catalyst: Polyaminobenzoate, Triethanolamine, Calcium phosphate, Bismuth subcarbonate, Zirconium oxide, Calcium oxide	Micro Mega, Besancon, USA
Endosequence BC sealer	Zirconium oxide, Calcium silicate, Calcium phosphate, Calcium hydroxide, Thickeners	Brasseler, Savannah, USA
BioRoot RCS	Powder: Tricalcium silicate, Zirconium oxide, Povidone Liquid: Aqueous calcium chloride solution, Polycarboxylate	Septodont, Saint Maur Des Fosses, France

Figure 7. AH-Plus

Figure 8. MM Seal

Figure 9. BioRoot RCS

Figure 10. Endosequence BC sealer

3.1.2. Root Canal Filling

A suitable standard gutta-percha (# 40, Diadent, Seoul, Korea) showing apical condensation was placed in the root canal of the master cone, and its suitability with the working length was checked. After removing the master cone from the canal, canal sealer prepared according to the manufacturer's recommendations (Figures 7, 8, 9, and 10) were placed on the canal walls with paper points, so that the covered area was 2-3 mm shorter than the working length. The apical part of the master gutta-percha cone was covered with sealer and the cone was placed in the canal at the working length. The spreader we selected was advanced through the channel by applying lateral pressure from the side of the master cone. In the gap created by the spreader, an auxiliary gutta-percha cone covered with canal sealer was placed. Condensation was performed by the spreader again and a new auxiliary gutta-percha cone was placed in the created space. The same operations were repeated until the spreader was unable to advance more than 1-2 mm from the canal entrance. The upper part of the gutta-percha cones was cut with the help of a heated excavator, at the level of the canal mouth. Vertical condensation was provided with a plugger suitable for the canal mouth. Canal mouths were sealed with Cavit-G (ESPE, D-8031 Seefeld, Germany) as a temporary filling material. All groups were filled in the same way.

After filling the root canals with cold lateral condensation method, mesio-distal and bucco-lingual radiographs (Figure 11, Figure 12, Figure 13 and Figure 14) were taken from each sample and it was checked whether there was any void space in the root canal fillings. It was evaluated that root canal filling was not adequate for 3 teeth in groups 1 and 2, 2 teeth in group 3 and 1 tooth in group 4. For this reason, root canal fillings were repeated for these teeth.

All samples were incubated for 1 week in a 100% humidified environment at 37 ºC to achieve complete hardening of root canal sealers.

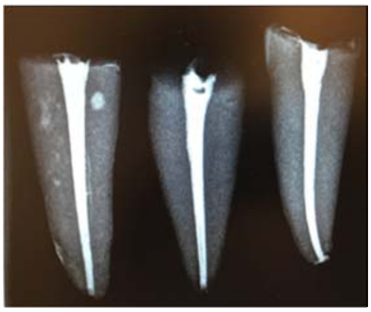

Figure 11. Radiographs after filling the root canals with AH Plus

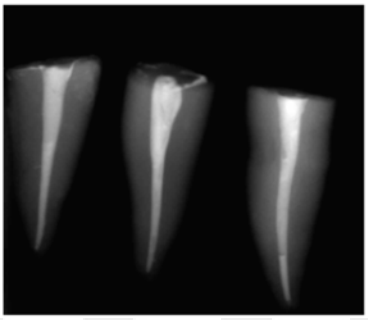

Figure 12. Radiographs after filling the root canals with MM Seal

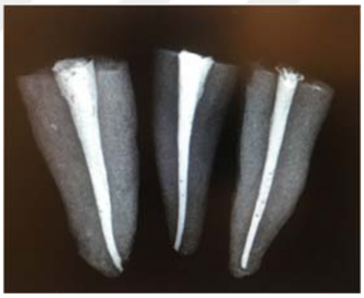

Figure 13. Radiographs after filling the root canals with Endosequence BC sealer

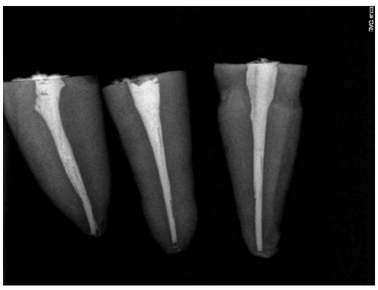

Figure 14. Radiographs after filling the root canals with BioRoot RCS

3.2. Micro-CT Imaging of Root Canal Fillings

A high-resolution micro-CT device (SkyScan 1172; Bruker micro-CT, Kontich, Belgium) located at İnönü University Scientific and Technological Research Center was used to scan the samples (Figure 15). The roots were wrapped in paper and placed in the sample tubes. The tubes were fixed on the sample bed in the SkyScan 1172 micro-CT device (Figure 16). Then the lid of the device was closed, and scanning was initiated.

Figure 15. SkyScan 1172 (SkyScan, Kontich, Belgium) micro-CT

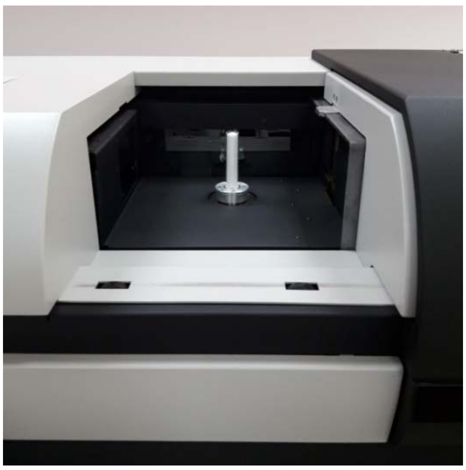

Figure 16. Placement of the tubes in the sample bed

The device has an X-ray source with adjustable voltage and various filters to adapt to objects of different density. The X-ray tube was operated with a 100-kV voltage and a current of 100 μA using an aluminum and copper filter with a scanning sectional thickness of 13.6 μm. Scanning was performed by applying an x-ray exposure time of 2600 ms with a 180° rotation angle around the vertical axis, by taking the averages of two frames. Each root scan took about 57 minutes. On average, 1134 sections were obtained from each root.

The obtained images were reconstructed with NRecon (v.1.6.4, Bruker-microCT) software with 65% beam-hardening correction, 3 smoothing and 0-0.48 attenuation coefficient values and necessary ring artifact corrections. Reconstructed sample images were repositioned In DataViewer (v.1.5.1, Bruker-microCT) software, as parallel as possible in both sagittal and coronal planes, and axial plane images were saved as a dataset. In order to make the measurements, the images were transferred to CTAn (v.1.13, Bruker-microCT) software and the volume of unfilled spaces in the root canal was measured. Using the same software, 3D models of root canal fillings, dentin and voids were created. CTVol (v.2.2.3, Bruker-microCT) software was used to visualize and examine the previously obtained three-dimensional models.

3.3. Measurement of Dentin Bond Strength of Canal Sealers (Push-Out Test)

Teeth were embedded in acrylic resin using cylinder molds (Figure 17). Three samples of approximately 1 mm thickness were then taken from coronal and middle thirds of each sample under water cooling with 0.3 mm thick diamond disks (Buehler, IL, USA) rotating at low speed using an Isomet device (IsoMet 4000, Buehler, IL, USA). The thicknesses of the obtained dentin discs were measured with digital calipers (Figure 19). Coronal surfaces of the sections were marked, and 48 specimens were obtained from each group (Figure 20, Figure 21, Figure 22 and Figure 23). Measurement of the dentin bonding strengths of canal sealers was performed in the Hard Tissue Laboratory of the Faculty of Dentistry, Yeditepe University. An Instron (Lloyd LRX; Lloyd Instruments Ltd, Fareham, UK) tester was used for the measurement (Figure 24). The apical face of the dentine disk was placed facing the side to which the force was to be applied. The cylindrical tip made of stainless steel with a diameter of 1 mm was mounted on the device and positioned so that it was only in contact with the filling material. Force was applied at a constant speed of 1 mm/min (Figure 25) until a sudden drop was observed in the load/time curve displayed on the computer (Figure 26). Using the Bluehill 3 data analysis program, the tensile breaking forces were recorded in Newton (N) and the bonding strength was calculated by turning these values into Megapascal (MPa) according to the following formula (54).

$$\text{Bond strength (MPa)} = \frac{\text{Maximum force (N)}}{\text{Bonding area of root canal filler (mm2)}}$$

The following formula was used to calculate the bond area of the sections (102).

$$\text{Bonding area of root canal filler} = 2\pi rh$$

According to the formula, r represents the root canal radius and h is the thickness of the section in mm. π was taken as 3.14.

Figure 17. Embedding teeth in acrylic resin

Figure 18. Isomet device

Figure 19. Measuring the thickness of dentin discs with digital calipers

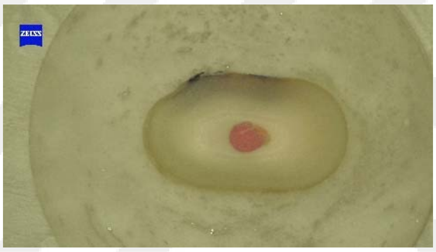

Figure 20. A dentin disc coronal image of Group 1

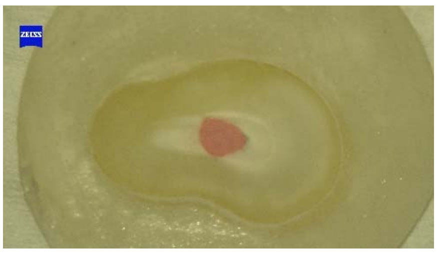

Figure 21. A dentin disc coronal image of Group 2

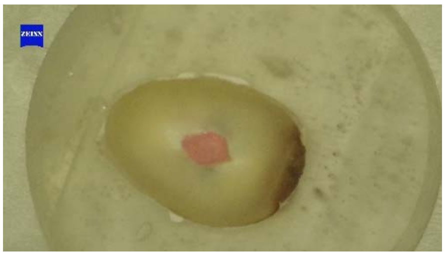

Figure 22. A dentin disc coronal image of Group 3

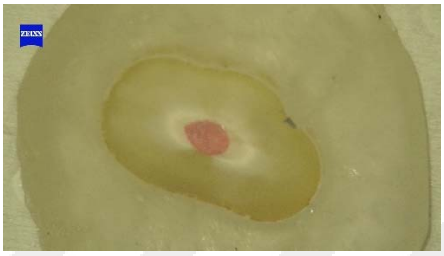

Figure 23. A dentin disc coronal image of Group 4

Figure 24. Instron

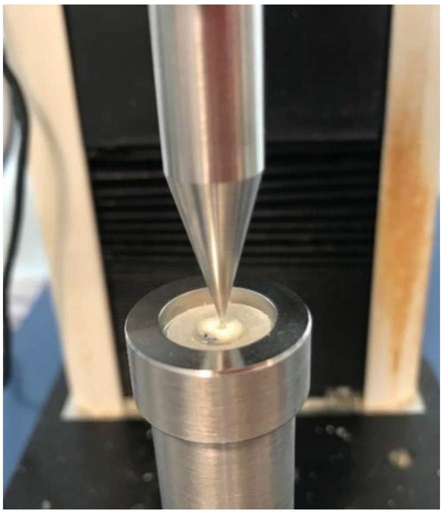

Figure 25. Application of thrust force

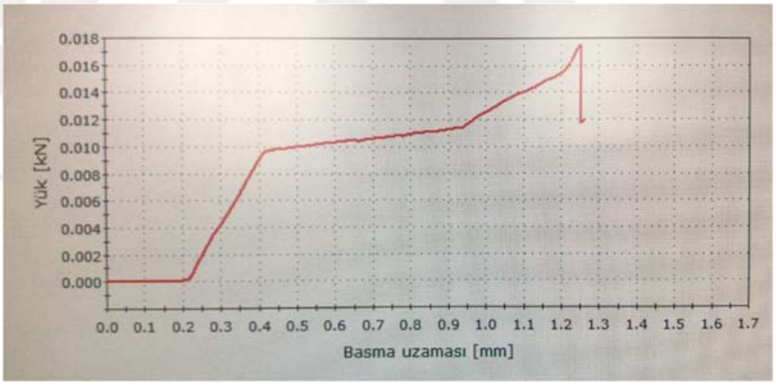

Figure 26. Load / time curve on computer screen

3.4. Statistical Analysis

The data were analyzed on a computer using the SPSS 25.0 (Statistical Packages of Social Sciences) program. Normal distribution fitness of the data was assessed by the Kolmogorov-Smirnov test. Descriptive statistics were expressed as mean ± standard deviation for continuous variables. The Kruskal Wallis test was used to compare the variables that were not normally distributed in more than two groups. Mann-Whitney U test was used for the binary comparison of statistically significant variables. The Friedman test was used to compare intra-group levels. Wilcoxon test was used for the binary comparison of statistically significant variables. The results were interpreted after performing a Bonferroni correction.

A significance level of 0.05 was used in the statistical tests and $P < 0.05$ was accepted as a significant difference whereas $P > 0.05$ indicated no difference.

4. RESULTS

In this study, we compared the presence of void spaces in the canals filled with 4 different root canal sealers using micro-CT technique and evaluated the dentin bonding strength of canal sealers by push-out test.

Power Analysis

Power analysis using Power and Sample size program revealed a sample size of at least n: 14 for each group. Based on this result, we determined a sample size of n: 16 for each group.

4.1. Resutls involving void spaces

The mean percentage values of void spaces determined in the coronal, middle and apical thirds of roots filled with four different root canal sealers are shown in Table 6.

Void spaces were compared within and between groups for coronal, middle and apical regions of roots.

Table 6. The mean percentage values of void spaces determined in the coronal, middle and apical thirds of roots filled with four different root canal sealers

Sample number	AH Plus			MM Seal			Endosequence BC sealer			BioRoot RCS		
	C	M	A	C	M	A	C	M	A	C	M	A
1	5,04	0,81	1,13	2,37	0,26	0,77	0,30	1,35	0,16	0,39	1,28	1,07
2	5,04	0,54	0,01	0,48	1,36	0,55	0,22	0,47	1,69	1,58	0,00	0,49
3	6,84	0,51	0,96	5,36	3,31	0,73	0,81	3,25	0,86	1,26	0,19	0,01
4	1,55	0,39	0,24	2,63	0,68	0,06	0,02	1,20	1,04	0,80	0,34	0,00
5	8,72	0,01	0,05	3,18	0,67	0,27	5,33	0,36	1,09	1,77	1,40	0,31
6	6,25	0,57	0,45	0,12	2,13	2,87	0,16	0,61	1,49	0,53	0,00	0,80
7	1,65	0,27	0,77	6,85	0,00	0,66	4,15	2,40	0,74	0,88	0,96	0,76
8	5,35	0,81	2,94	1,19	0,54	1,64	0,66	0,11	0,26	0,39	1,34	0,94
9	3,48	0,05	0,09	0,20	0,15	0,20	0,03	1,06	0,21	0,24	0,84	2,17
10	1,60	0,12	0,00	10,7	0,03	2,02	1,16	3,25	0,65	0,32	0,72	2,19
11	2,96	0,95	1,19	5,23	5,79	1,27	0,47	0,63	0,73	5,10	4,14	0,50
12	0,51	0,00	0,47	5,72	1,53	0,71	0,05	0,61	0,78	2,51	0,68	1,16
13	2,41	0,29	0,52	2,90	0,39	0,35	2,47	1,33	0,11	2,92	0,39	0,00
14	0,11	0,48	0,11	3,76	1,28	1,68	0,02	0,00	1,62	1,58	1,52	2,02
15	1,54	2,22	1,38	4,33	0,01	0,65	0,05	0,26	0,79	1,46	0,15	0,36
16	0,05	5,36	0,53	0,34	0,07	1,51	0,14	0,03	0,06	0,00	0,00	0,00
Average	3,32	0,84	0,68	3,46	1,01	1,00	1,00	1,06	0,77	1,36	0,87	0,80

4.1.1. Results of intra-group comparisons

4.1.1.1. Results involving AH Plus canal sealer

Examples of micro-CT images obtained from the coronal, middle and apical thirds of roots filled with AH Plus canal sealer are shown in Figures 27 and 28.

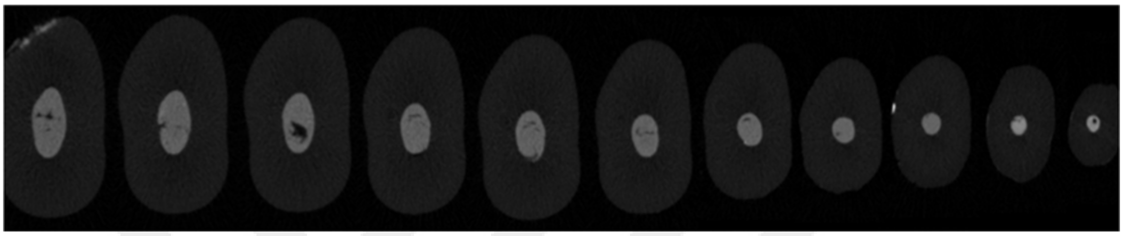

Figure 27. Micro-CT images of coronal, mid and apical thirds of AH Plus group

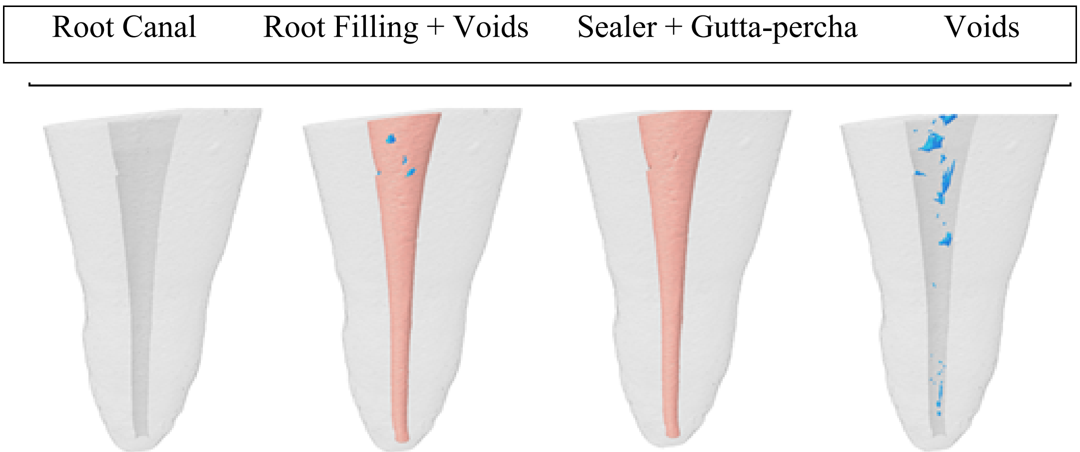

Figure 28. Three dimensional reconstruction of AH Plus group

The mean percentage values, standard deviations, and P values obtained from the Friedman test for the void volumes formed in the coronal, middle, and apical thirds of roots filled with AH Plus canal sealer are shown in Table 7.

Table 7. The void volume results of the AH Plus group

Group		N	Average	St. Deviation	P value
AH Plus	Apical	16	,6825	,75259	0,001*
	Middle	16	,8411	1,31972	
	Coronal	16	3,3237	2,60957	

As seen in the table, there is a statistically significant difference between the three regions in terms of void space in the coronal, middle, and apical third as a result of the Friedman test performed on the void spaces detected in the coronal, middle, and apical thirds of the roots filled with AH Plus root canal sealer ($P < 0.05$).

Table 8. Binary comparison of statistically significant variables

	Apical-Middle	Apical-Coronal	Coronal-Middle
AH Plus	1.000	0,001*	0,001*

Bilateral comparisons were made using the Wilcoxon test to assess the level of difference between variables in the groups with significant differences. The results were interpreted after performing a Bonferroni correction. A significant difference was found between the coronal and apical, and coronal and middle levels in the AH Plus group, and the coronal value was larger than the other levels.

4.1.1.2. Results involving MM Seal canal sealer

Examples of micro-CT images obtained from the coronal, middle, and apical thirds of roots filled with MM Seal canal sealer are shown in Figure 29 and Figure 30.

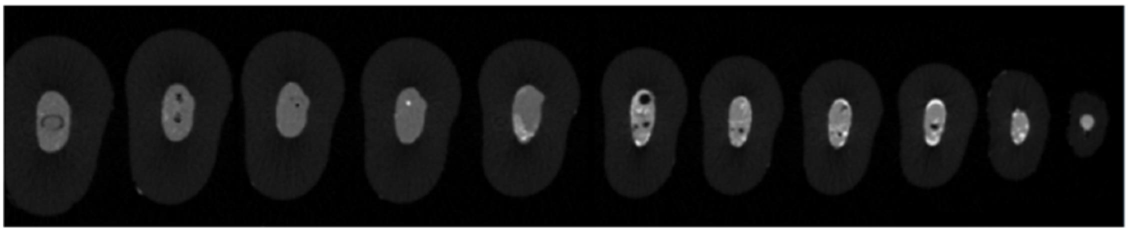

Figure 29. Micro-CT images of coronal, mid and apical thirds of MM Seal group

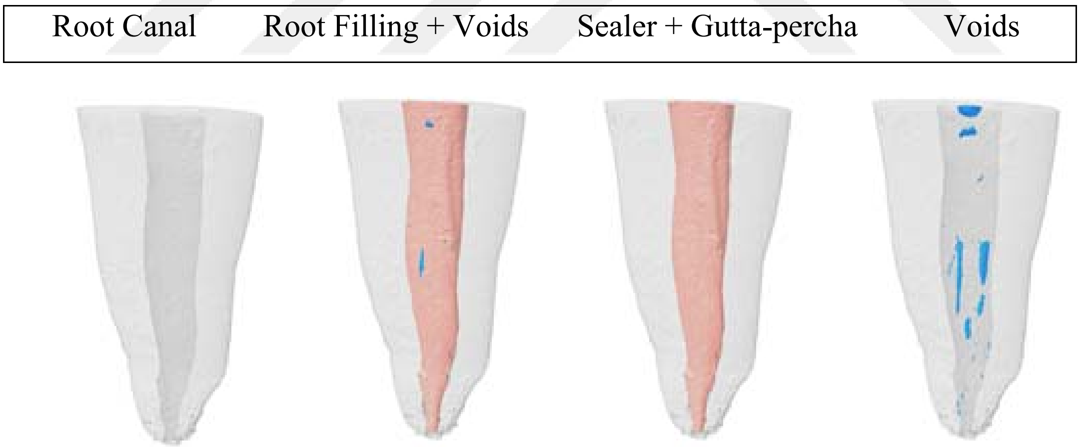

Figure 30. Three dimensional reconstruction of MM Seal group

The mean percentage values, standard deviations, and P values obtained from the Friedman test for the void spaces formed in the coronal, middle, and apical thirds of roots filled with MM Seal canal sealer are shown in Table 9.

Table 9. The void volume results of the MM Seal group

<table>
<tr><td colspan="2">Group</td><td>N</td><td>Average</td><td>St. Deviation</td><td>P value</td></tr>
<tr><td rowspan="3">MM Seal</td><td>Apical</td><td>16</td><td>1,0014</td><td>,76946</td><td rowspan="3">0,026*</td></tr>
<tr><td>Middle</td><td>16</td><td>1,0179</td><td>1,43033</td></tr>
<tr><td>Coronal</td><td>16</td><td>3,4677</td><td>2,88659</td></tr>
</table>

As seen in the table, there is a statistically significant difference between the three regions in terms of void spaces in the coronal, middle and apical thirds based on the Friedman test performed for mean percentage values of void spaces detected in the coronal, middle and apical thirds of roots filled with MM Seal canal sealer ($P < 0.05$).

Table 10. Binary comparison of statistically significant variables

	Apical-Middle	Apical-Coronal	Coronal-Middle
MM Seal	0,536	0,052	0,010*

Bilateral comparisons were made using the Wilcoxon test to assess the level of difference in variables showing significant differences within groups. The results were interpreted after performing a Bonferroni correction. A significant difference was found between the coronal and middle levels in the MM Seal group, and the coronal value was larger in this group.

4.1.1.3. Results involving Endosequence BC sealer

Examples of micro-CT images obtained from the coronal, middle, and apical thirds of roots filled with Endosequence BC sealer are shown in Figure 31 and Figure 32.

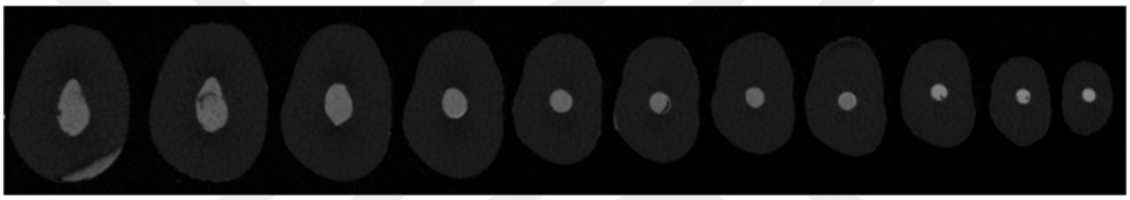

Figure 31. Micro-CT images of coronal, mid and apical thirds of Endosequence BC Sealer group

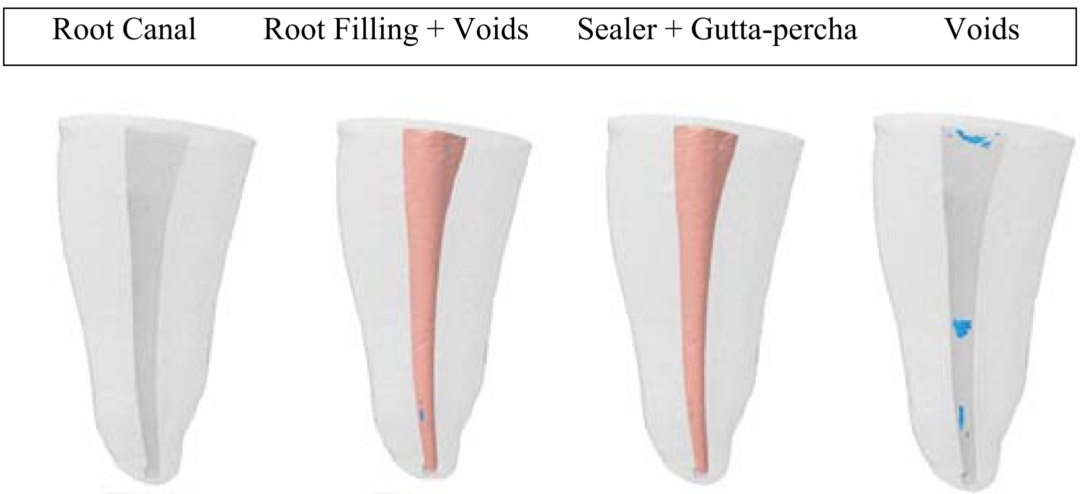

Figure 32. Three dimensional reconstruction of Endosequence BC sealer group

The mean percentage values, standard deviations, and P values obtained from the Friedman test for the void spaces formed in the coronal, middle, and apical thirds of roots filled with Endosequence BC sealer are shown in Table 11.

Table 11. The void volume results of the Endosequence BC sealer group

Group		N	Average	St. Deviation	P value
Endosequence BC sealer	Apical	16	,7722	,52801	0,646
	Middle	16	1,0633	1,05625	
	Coronal	16	1,0037	1,60419	

.

As seen in the table, there is no difference between the three regions in terms of void spaces in the coronal, middle and apical thirds based on the Friedman test performed for mean percentage values of void spaces detected in the coronal, middle and apical thirds of roots filled with Endosequence BC sealer (P > 0.05). Percentage of void spaces is higher in the middle third of the root compared to other regions. Smallest values were obtained in the apical third.

4.1.1.4. Results involving BioRoot RCS canal sealer

Examples of micro-CT images obtained from the coronal, middle, and apical thirds of roots filled with BioRoot RCS canal sealer are shown in Figure 33 and Figure 34.

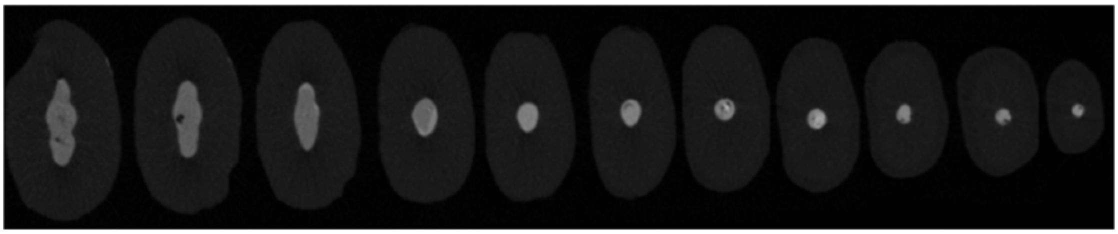

Figure 33. Micro-CT images of coronal, mid and apical thirds of BioRoot RCS group

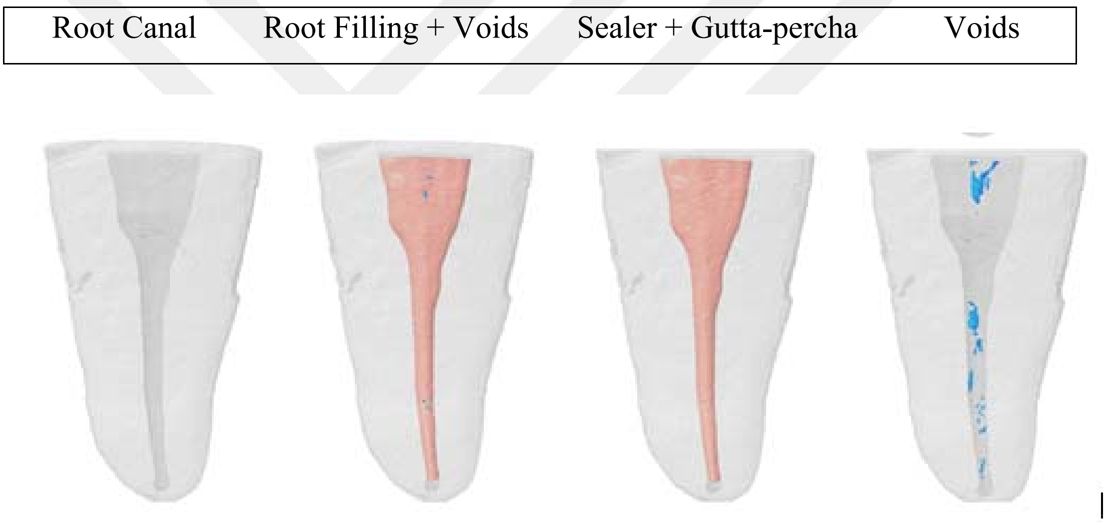

Figure 34. Three dimensional reconstruction of BioRoot RCS group

The mean percentage values, standard deviations, and P values obtained from the Friedman test for the void spaces formed in the coronal, middle, and apical thirds of roots filled with BioRoot RCS canal sealer are shown in Table 12.

Table 12. The void volume results of the BioRoot RCS group

Group		N	Average	St. Deviation	P value
BioRoot RCS	Apical	16	,8036	,76137	0,444
	Middle	16	,8775	1,02009	
	Coronal	16	1,3641	1,30119	

As seen in the table, there is no difference between the three regions in terms of void spaces in the coronal, middle and apical thirds based on the Friedman test performed for mean percentage values of void spaces detected in the coronal, middle and apical thirds of roots filled with BioRoot RCS canal sealer ($P > 0.05$). Percentage of void spaces is higher in the coronal third of the root compared to other regions. Smallest values were obtained in the apical third.

4.1.2. Resuls of inter-group comparisons

4.1.2.1. Void Space Evaluation in Root Apical Thirds of All Groups

The mean percentage values, standard deviation values, and Kruskal-Wallis H test results of the void spaces detected in the apical third of roots filled with four different root canal sealers are shown in Table 13.

Table 13. Apical third results and Kruskal-Wallis H test results in all groups

	Group	N	Average	St. Deviation	95% Confidence Interval		P value
					Lower limit	Upper limit	
Apical third void volume (%)	AH Plus	16	,682476	,7525833	,281453	1,083499	0,542
	MM Seal	16	1,001374	,7694640	,591355	1,411392	
	Endosequence BC sealer	16	,772210	,5280281	,490844	1,053576	
	BioRoot RCS	16	,803577	,7613628	,397876	1,209279	
	Total	64	,814909	,7028547	,639341	,990477	
Apical third material volume (%)	AH Plus	16	99,317524	,7525833	98,916501	99,718547	0,542
	MM Seal	16	98,998626	,7694640	98,588608	99,408645	
	Endosequence BC sealer	16	99,227790	,5280281	98,946424	99,509156	
	BioRoot RCS	16	99,196423	,7613628	98,790721	99,602124	
	Total	64	99,185091	,7028547	99,009523	99,360659	

As seen in the table, there was no significant difference in the void spaces detected in the apical thirds of four groups ($P > 0.05$), and the largest void space in the apical third was found in the MM Seal group (1.00%), whereas the smallest void space was found in the AH Plus group (0.68%).

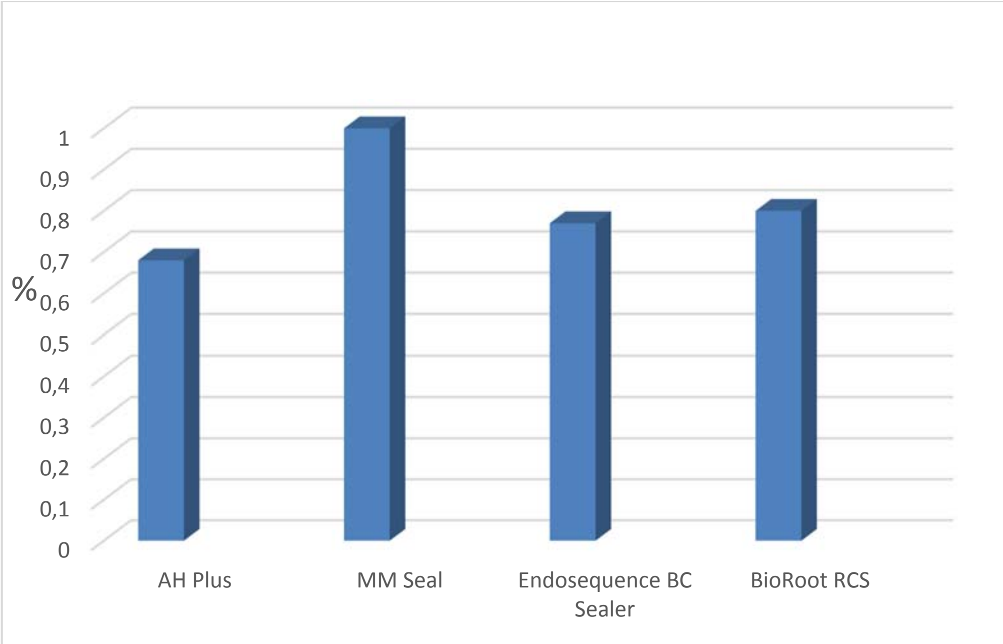

Figure 35. The mean values of the void volumes formed in apical thirds of all groups

4.1.2.2. Void Space Evaluation in Root Middle Thirds of All Groups

The mean percentage values, standard deviation values, and Kruskal-Wallis H test results of the void spaces detected in the middle third of roots filled with four different root canal sealers are shown in Table 14.

Table 14. Middle third results and Kruskal-Wallis H test results in all groups

	Group	N	Average	St. Deviation	95% Confidence Interval		P value
					Lower Limit	Upper Limit	
Middle third void volume (%)	AH Plus	16	,841088	1,3197208	,137858	1,544317	0,806
	MM Seal	16	1,017864	1,4303337	,255693	1,780035	
	Endosequence BC sealer	16	1,061673	1,0606728	1,186538	1,689885	
	BioRoot RCS	16	,877460	1,0200886	,333893	1,421027	
	Total	64	0,945021	1,2055672	,410928	1,333115	
Middle third material volume (%)	AH Plus	16	99,158912	1,3197208	98,455683	99,862142	0,806
	MM Seal	16	98,982136	1,4303337	98,219965	99,744307	
	Endosequence BC sealer	16	98,948327	1,0606728	98,310115	99,186538	
	BioRoot RCS	16	99,122540	1,0200886	98,578973	99,666107	
	Total	64	99,047979	1,2055672	99,666885	99,589072	

As seen in the table, there was no significant difference in the void spaces detected in the middle thirds of four groups ($P > 0.05$), and the largest void space in the apical third was found in the Endosequence BC Sealer group (1.06%), whereas the smallest void space was found in the AH Plus group (0.84%).

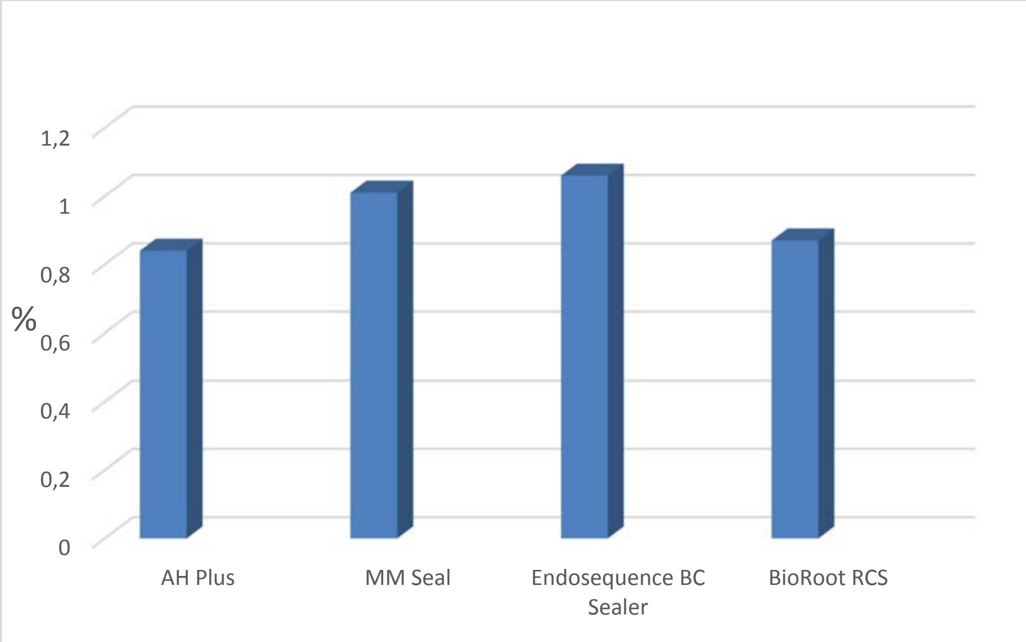

Figure 36. The average values of the void volumes formed in the middle thirds of all groups

4.1.2.3. Void Space Evaluation in Root Coronal Thirds of All Groups

The mean percentage values, standard deviation values, and Kruskal-Wallis H test results of the void spaces detected in the coronal third of roots filled with four different root canal sealers are shown in Table 15.

Table 15. Coronal third results and Kruskal-Wallis H test results in all groups

	Group	N	Avearage	St. Deviation	95% Confidence Interval		P value
					Lower Limit	Upper Limit	
Coronal third void volume (%)	AH Plus	16	3,3292338	2,6156770	1,978824	5,405851	0,002*
	MM Seal	16	3,478080	2,8947732	1,348737	5,087423	
	Endosequence BC sealer	16	1,003698	1,6041896	,148885	1,858510	
	BioRoot RCS	16	1,364090	1,3011690	,670746	2,057434	
	Total	64	2,289551	2,1190540	1,690518	3,448585	
Coronal third material volume (%)	AH Plus	16	96,687662	2,6156770	94,594149	98,021176	0,002*
	MM Seal	16	96,531920	2,8947732	94,912577	98,651263	
	Endosequence BC sealer	16	98,996302	1,6041896	98,141490	99,851115	
	BioRoot RCS	16	98,635910	1,3011690	97,942566	99,329254	
	Total	64	97,770449	2,1190540	96,551415	98,309482	

As seen in the table, there is a statistically significant difference between the four groups in terms of the void spaces detected in the middle third ($P < 0.05$).

The results of the binary comparisons with the Mann-Whitney U test performed in order to determine the groups causing the statistical differences in coronal third void spaces are shown in Table 16.

Table 16. Mann-Whitney U test results of coronal third between groups

	Coronal third void volume (%)	Coronal third material volume (%)
MM Seal - Endosequence BC sealer	0,001*	0,001*
MM Seal - BioRoot RCS	0,049*	0,049*
MM Seal - AH Plus	0,962	0,962
BioRoot RCS-Endosequence BC sealer	1,000	1,000
Endosequence BC sealer - AH Plus	0,001*	0,001*
BioRoot RCS - AH Plus	0,056	0,056

Void space in the Endosequence BC sealer group (1.00%) was significantly lower than the MM Seal (3.47%) and AH Plus (3.32%) groups ($P < 0.05$). Void space in the BioRoot RCS group (1.36%) was significantly lower than the MM Seal (3.47%) group ($P < 0.05$).

Largest void space values in the coronal third were obtained in the MM Seal group (3.47%), whereas the smallest values were obtained in the Endosequence BC sealer group (1.00%).

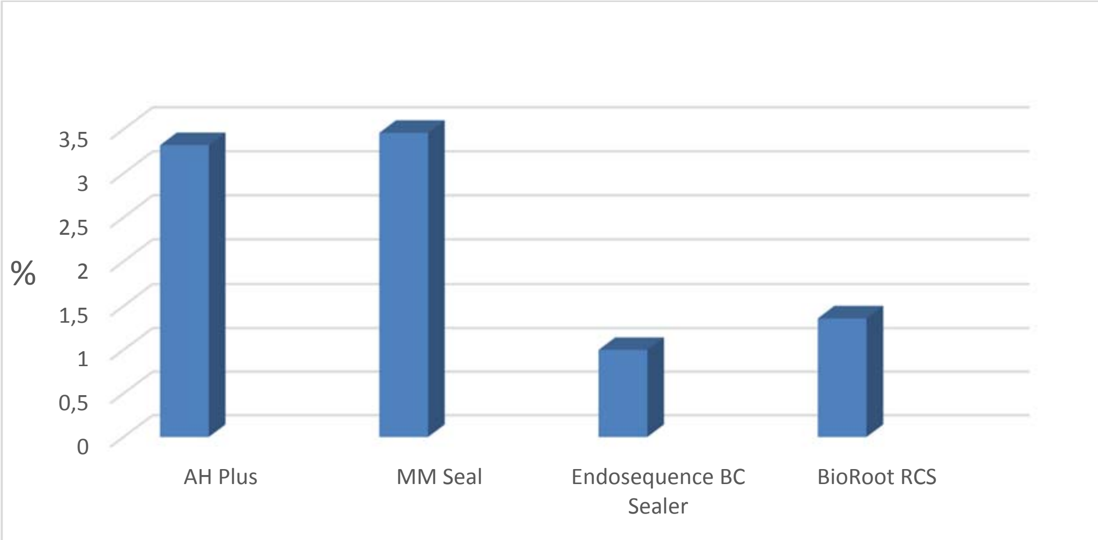

Figure 37. The average values of the void volumes formed in the middle thirds of all groups

4.1.2.4. Total Void Space Evaluation of All Groups

The mean percentage values, standard deviation values, and Kruskal-Wallis H test results of the total void spaces detected in the roots filled with four different root canal sealers are shown in Table 17.

Table 17. All third results and Kruskal-Wallis H test results in all groups

	Group	N	Average	St. Deviation	95% Confidence Interval		P value
					Lower limit	Upper limit	
All third void volume (%)	AH Plus	16	1,7643	1,29505	1,0742	2,4544	0,142
	MM Seal	16	1,8192	,96490	1,3050	2,3333	
	Endosequence BC sealer	16	1,1154	,91481	,6280	1,6029	
	BioRoot RCS	16	1,3998	1,02106	,8557	1,9439	
	Total	64	1,5247	1,07312	1,2566	1,7927	
All third void volume (%)	AH Plus	16	98,2357	1,29505	97,5456	98,9258	0,142
	MM Seal	16	98,1808	,96490	97,6667	98,6950	
	Endosequence BC sealer	16	98,8846	,91481	98,3971	99,3720	
	BioRoot RCS	16	98,6002	1,02106	98,0561	99,1443	
	Total	64	98,4753	1,07312	98,2073	98,7434	

As seen in the table, there was no significant difference in the total void spaces detected in the roots of four groups ($P > 0.05$), and the largest void space in the entire root was found in the MM Seal group (1.81%), whereas the smallest void space was found in the Endosequence BC Sealer group (1.11%).

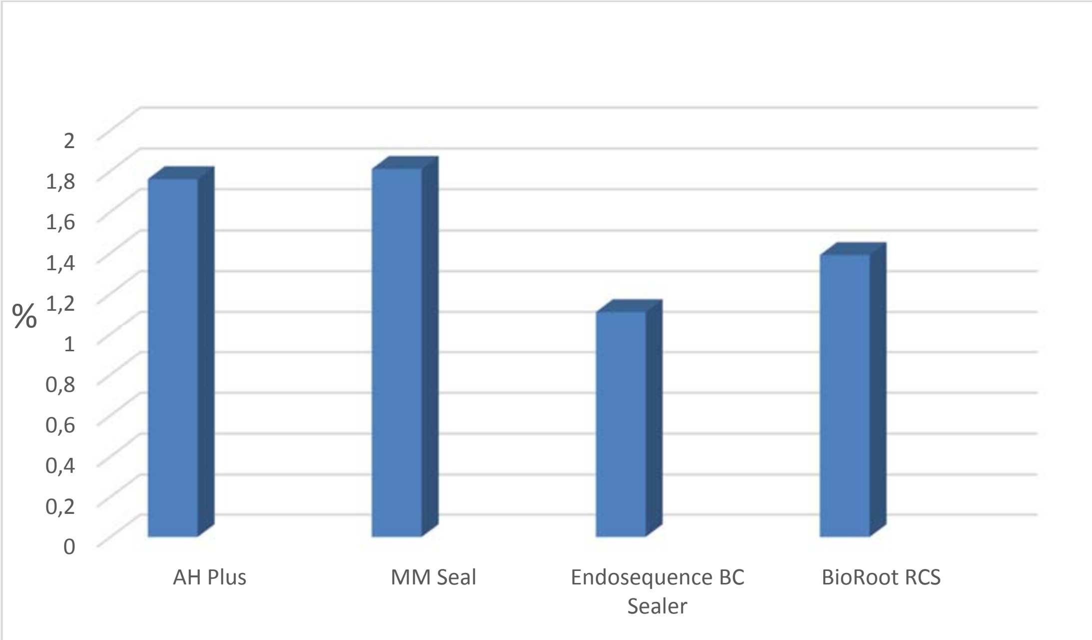

Figure 38. The average values of the void volumes formed in the all thirds of all groups

4.2. Bond Strength Values

The MPa values of the samples in the study groups determined by push-out test are shown in Table 18, Table 19, Table 20 and Table 21.

Table 18. Push-out values for the samples in the AH Plus group

Sample	Maximum Loading (MPa)
1	1,87
2	1,41
3	2,19
4	1,74
5	1,19
6	1,18
7	1,78
8	1,55
9	1,77
10	1,39
11	2,11
12	1,53
13	2,30
14	1,5
15	1,01
16	1,97
17	2,16
18	2,21
19	1,64
20	1,45
21	1,57

22	1,46
23	1,49
24	1,05
25	1,53
26	1,62
27	2,02
28	1,97
29	2,35
30	2,14
31	1,14
32	1,69
33	1,25
34	1,73
35	1,51
36	2,21
37	1,67
38	1,32
39	1,78
40	1,81
41	1,39
42	1,32
43	1,20
44	1,45
45	1,22
46	1,44
47	1,39
48	1,32
Avearage	1,62

Table 19. Push-out values for the samples in the MM Seal group

Sample	Maximum Loading (MPa)
1	1,68
2	1,13
3	0,67
4	1,19
5	1,38
6	0,92
7	1,27
8	0,49
9	1,22
10	1,38
11	1,15
12	1,67
13	1,67
14	1,31
15	0,87
16	2,08
17	1,04
18	1,08
19	1,35
20	1,09
21	0,61
22	0,78
23	0,90
24	1,16
25	0,76
26	0,95
27	1,33
28	0,85

29	1,23
30	0,90
31	1,30
32	1,46
33	1,21
34	0,65
35	1,04
36	0,91
37	1,08
38	1,26
39	1,25
40	1,86
41	1,43
42	1,32
43	1,59
44	0,87
45	1,23
46	1,27
47	1,10
48	1,23
Average	1,17

Table 20. Push-out values for the samples in the Endosequence BC Sealer

Sample	Maximum Loading (MPa)
1	1,33
2	2,40
3	2,5
4	1,36
5	1,46
6	1,54
7	1,51
8	1,27
9	1,83
10	2,27
11	1,51
12	2,21
13	1,86
14	1,49
15	1,92
16	2,05
17	1,73
18	1,71
19	2,08
20	1,32
21	1,83
22	1,92
23	1,35
24	1,86
25	1,12
26	1,14
27	1,59
28	1,65

29	2,13
30	1,91
31	2,02
32	2,07
33	2,00
34	1,71
35	1,91
36	2,18
37	2,38
38	1,67
39	1,57
40	1,43
41	1,91
42	1,86
43	2,22
44	1,68
45	1,84
46	2,16
47	1,99
48	1,59
Average	1,79

Table 21. Push-out values for the samples in the BioRoot RCS

Sample	Maximum Loading (MPa)
1	1,42
2	2,38
3	1,30
4	1,40
5	1,71
6	2,00
7	1,49
8	1,28
9	1,89
10	1,60
11	1,86
12	1,79
13	1,28
14	1,79
15	2,19
16	1,60
17	1,28
18	1,78
19	2,11
20	1,91
21	1,20
22	1,46
23	1,43
24	1,70
25	1,52
26	1,60
27	1,67
28	1,48

29	1,55
30	1,65
31	1,89
32	1,49
33	1,95
34	1,92
35	1,40
36	1,70
37	1,02
38	1,26
39	1,67
40	2,03
41	1,81
42	1,95
43	1,86
44	1,17
45	1,52
46	1,87
47	1.42
48	1,53
Average	1,64

Table 22. Results for push-out bonding strength

Maximum MPa				
	N	Average	St. Deviation	P value
AH Plus	48	1,6248	,35322	0,000*
BioRoot RCS	48	1,6413	,28949	
EndoSequence BC Sealer	48	1,7925	,33821	
MM Seal	48	1,1702	,32401	
Total	192	1,5572	,39972	

* P < 0.05 is statistically significant. P values were obtained by.Kruskal Wallis test.

When the values of the variables were compared between the groups, a significant difference was found between the groups in terms of Maximum MPa values (P < 0.05).

Table 23. Binary comparison of statistically significant variables

Comparison of groups (p values)	Maximum MPa
AH Plus- BioRoot RCS	1,000
AH Plus- EndoSequence BC Sealer	0,177
AH Plus- MM Seal	0,000*
BioRoot RCS- EndoSequence BC Sealer	0,759
BioRoot RCS- MM Seal	0,000*
EndoSequence BC Sealer -MM Seal	0,000*

* P < 0.05 is statistically significant. P values were obtained by Mann-Whitney U test Bonferroni correction.

Binary comparisons were performed to specify the cause of significant difference between groups, and significant differences were found between AH Plus-MM Seal, BioRoot RCS-MM Seal, and EndoSequence BC Sealer-MM Seal groups ($P < 0.05$). MM Seal group exhibited a weaker bond strength (1.17) compared to the other groups.

Although there is no difference between three groups in terms of bond strength ($P > 0.05$), highest values were detected in the Endosequence BC sealer group (1.79).

4.3. Relationship Between Dentin Bonding Strength of Root Canal Sealers and Void Space Values

A correlation analysis was performed to determine whether there was a relationship between root dentin bonding strengths of the root canal sealers and the void space values. Pearson correlation analysis performed is shown in Table 24.

Table 24. Correlation analysis results between the root dentin bonding strength values (MPa) and void space values (%) of root canal sealers

		Apical third void volume	Middle third void volume	Coronal third void volume	All third void volume
Maximum Loading (MPa)	r	-,073	-,002	-,295*	-,223
	P	,568	,985	,019	,077
	n	64	64	64	64
Apical third void volume	r		,144	,045	,150
	P		,255	,724	,238
	n		64	64	64
Middle third void volume	r			,014	,303*
	P			,916	,015
	n			64	64
Coronal third void volume	r				,630**
	P				,000
	n				64

*(P<0,05), r: Pearson correlation coefficient

There was a weak negative correlation between the maximum loading (MPa) and the coronal third void space measurements (r = -0.295, P = 0.019). It can be said that as the MPa value increases, the coronal third void space measurement decreases to a weaker extent.

Table 25. Interpretation of Pearson correlation coefficients

Correlation Coefficient	**Interpretation**
0.8-1.0	Very strong relationship
0.6-0.8	Strong relationship
0.4-0.6	Intermediate relationship
0.2-0.4	Weak relationship
0.0-0.2	Very weak or no relationship

5. DISCUSSION

To maintain the level of disinfection achieved after shaping and irrigation of the root canal system and to prevent the passage of bacteria through the canal, the canal system must be sealed in a three-dimensional manner (123).

Root canal filler should be well adhered to the canal walls, and the entirety of the canal should be hermetically and homogeneously filled with gutta-percha material by using a minimum amount of root canal sealer and maximum amount of core material (123). Strong adhesion of root canal sealers to the dentin and core material is one of the properties that canal sealers should possess. Through adhesion of root canal sealers to dentin and gutta-percha, formation of cavities in the root canal filling can be prevented, thereby creating a better sealing (12). The presence of cavities in the root canal, either in the apical or coronal region, may lead to a pathway for leakage. These pathways and passages may cause bacterial reproduction, development of a new infection or recurrence of the disease after canal treatment. In the presence of cavities in the root canal filling, the likelihood of post-treatment recurrence is greater (124).

Different root canal sealers and filling techniques are used in a three-dimensional hermetic root canal filling, which is the final stage of a successful endodontic treatment (144). Root canal sealers that are used in root canal treatments and their properties are one of the important factors affecting the success of treatment. Root canal filleing sealers enhances gutta-percha adaptation by filling the region between the filler material and dentin wall, irregularities in the canal, and lateral and accessory canals (27). It has been reported that the leakages in root canals occur in the root canal sealer or in the sealer-dentin or sealer-gutta-percha interface as the sealer shows resorption (46). In our study, AH Plus and MM Seal root canal filling sealers and newly developed Endosequence BC Sealer and BioRoot RCS canal filling sealers were examined. AH Plus was found to be more successful than other root canal sealers in studies examining the bonding strength of canal sealers and has been accepted as the gold standard (74, 152). There is limited number of studies in the literature investigating the bonding strength of newly developed Endosequence BC sealer (74, 79, 83), and no studies on BioRoot RCS. The number of studies evaluating the effect of Endosequence BC Sealer and BioRoot RCS sealers on canal fill quality is very limited. Therefore, we chose to use Endosequence BC Sealer and BioRoot RCS sealers in our study to address this gap in the literature.

According to the results of the Power analysis performed for our study, 14 observations in each group with 80% power and 56 observations in total would be enough. It is important to determine the number of samples appropriately to reduce the risk of type 1 and type 2 errors (153). For this reason, with the aim of increasing the statistical efficiency, each group was formed to include 16 teeth in our study.

In our study, we used extracted human teeth to mimic clinical conditions. In similar studies investigating bonding strengths of root canal sealers (74, 79, 108) and evaluating void spaces in root canal fillings (84, 94, 146), extracted teeth were preferred over acrylic blocks. However, the use of extracted human teeth causes difficulties in achieving standardization (154). To ensure standardization, the roots of the extracted teeth should be of similar diameter and size, of similar length, and of similar apical foramen diameter (155). To ensure the standardization of the teeth used in our study, the crowns of all the sample teeth were removed from the enamel-cement border with 15 mm roots and the teeth were randomly stratified into groups by measuring the buccolingual diameters of the root in the collar region. In addition, all samples were shaped using the same technique with the same tools, and apical foramen diameters were standardized. Lower premolar teeth were preferred due to their similar anatomy, and the teeth having a uniform, single and wide root canal. Due to the wide canal diameters, it was thought that the ratio of filling material to be filled in the canal would increase and allow for a better comparison.

It has been reported that irrigation solutions used in endodontics have adverse effects on the adhesion of resin-containing canal sealers to root canal dentin. NaOCl acts as an oxidation agent and oxidizes some components of the dentin matrix. Oxygen prevents polymerization of resins. For these reasons, the use NaOCl as the last irrigation agent is not recommended in endodontic treatment (126). In our study, we used 5 ml distilled water as a final wash to eliminate the effects of washing solutions.

As a result of the effects of instruments used in endodontic shaping of root canals on the canal wall, a 1-5 μm thick smear layer forms (127). The smear layer consists of dentin, predentin, odontoblast extensions, pulpa residues, bacteria and necrotic debris. No consensus has been reached on the removal or preservation of the smear layer formed during root canal treatment (128). Removal of the smear layer has been shown to increase the ability of the canal sealer to attach to the dentin tubules and thus to the canal walls (129, 130). There are, however, studies arguing that removal of the smear layer increases dentin permeability, disrupting the covering property of root canal sealers, and causes bacterial proliferation in the dentin tubules (131, 132). In our study, we considered that the smear layer would have a negative effect on the bonding of root canal sealer to the canal wall and opted to remove the smear layer.

NaOCl solution, which is often used as an irrigating agent in endodontic treatment, can remove organic residues and predentin. However, when NaOCl is used alone, the smear layer cannot be removed completely because NaOCL cannot act on the inorganic structure. For this reason, different irrigation solutions must be used together to remove organic and inorganic components. Combined use of NaOCl and EDTA has been reported to be effective in removing the smear layer (130). For this reason, we washed the canals with 5 ml of 17% EDTA and 5 ml of 5% sodium hypochlorite for 1 minute to remove the smear layer from the root canals after shaping was completed.

Different canal filling techniques are used during endodontic treatment. Among these techniques, the lateral condensation technique is the most commonly used root canal filling technique in clinical settings (100). Yasameen and Hussain (2011) found that the bonding strength of lateral condensation technique was significantly higher than the single cone technique, and attributed this result to increased polymerization shrinkage and the resulting disruption in bonding due to the increased sealer thickness in the single cone technique (156). Çelikten et al. (2015) filled root canals with Endosequence BC sealer using single cone, lateral condensation and Thermafil filling techniques. The apical covering ability of root canal filling techniques was compared using micro-CT technique. As a result, although there was no statistical difference between the techniques in terms of void space, the largest void space was found in the single cone technique and the least space was found in the Thermafil technique (157). Keles et al. (2014) compared the filling material and void space percentages in canal fillings made by lateral condensation and hot vertical condensation techniques. As a result, a significantly higher gutta-percha percentage and less void space were observed in the canals filled with the hot vertical condensation technique (145). However, hot vertical condensation technique affects properties such as operating time and fluidity of canal sealers (91). Operating time and fluidity properties of the iRoot SP sealer, the contents of which is similar to Endosequence BC Sealer, showed a significant decrease at high temperature (158). Camileri (2015) reported that the operating time of BioRoot RCS sealer was shortened in hot vertical condensation technique as a result of exposure to heat, and film thickness increased (91). Despite the advantages of the hot vertical condensation technique, the reason why we did not use the hot vertical condensation technique in our study can be explained by the two studies mentioned above.

Studies have shown that in the canal fillings made by the lateral condensation technique, void spaces may form due to resorption of cavities not filled by canal sealer or areas filled by canal sealer. This will reduce the quality of the canal fill (159). In our study, we investigated the effect of bioceramic based canal sealers, which have entered our lives in recent years, on the canal fill quality and compared them with traditional canal sealers.

The quality of root canal fillings was assessed using different methods. SEM, fluid filtration technique, electrochemical methods, radioisotope, radiography technique and bacterial penetration are some of these methods (3, 155, 160-162). Dye penetration, fluid transport and section analysis are also among the techniques used (155). Examination of root canal filling quality by determining the areas of gutta-percha, canal sealer and void spaces by obtaining horizontal sections from the samples may disrupt the integrity of the canal filling material (163). In the electrochemical method, accumulation of corrosion debris on the copper anode can block the flow of ions and the amount of leakage can be measured incorrectly (36). In the radioisotope method, the disadvantages are possible health risks for humans and difficult working conditions (164). In radiographic studies, even a canal filling with unsuccessful condensation and adaptation can give the image of a successful canal fill due to the angle of X-rays (165). In vitro leakage studies cannot accurately reflect clinical outcomes (155). None of the leakage techniques used so far has been universally accepted. Some deficiencies have been identified in all the methods described above. For this reason, we used micro-CT in our study, which enables us to obtain three-dimensional images.

Micro-CT device is used in many studies in dental medicine researches. These are; assessment of root canal morphology, assessment of root canal preparation, irrigation and debris accumulation, tissue engineering, root tip surgery, evaluation of root canal fillings, anthropological studies, assessment of implants and bone around implants, and mineral concentrations of teeth (140). The use of micro-CT technique is recommended to avoid the negative aspects of other techniques. It is stated that the micro-CT technique does not exhibit the disadvantages of other techniques used in the evaluation of root canal filling because it does not damage the specimens. It is possible to re-scan the specimens so that the changes in the canal fill can be determined (8). In view of these considerations, we chose micro-CT imaging technique to evaluate the qualities of root canal fillings in our study.

Bond strength tests are commonly used techniques for examining the bonding effectiveness of root canal sealers to root dentin. However, there is no standardization of bonding strength tests and choosing a technique is a matter of discussion (166). The use of the microtensile method was not considered appropriate in evaluating root canal sealers with low bonding strength (14). It has been reported that the fracture caused by the push-out test is parallel to the bonding surface with the root dentin and this fracture pattern reflects the clinical condition better. In addition, it has been reported that the push-out test is more reliable when compared with other bonding strength tests, and sample preparation success is lower in the microtensile test (102). For these reasons, we used the push-out test method in our study.

The friction force generated in the push-out test can cause misinterpretation of the results. The use of 1 mm thick sections has been proposed to prevent the resulting frictional force (167). However, Gesi et al. (2005) reported that using 2 mm thick sections could prevent early deteriorations that occurred in root canal sealer bonding (168). In our study, we also used 1 mm thick sections to reduce the non-homogeneous stress distribution due to frictional force. Thus, we reduced friction by reducing the contact area of the root canal filling material.

In our study, the thickness of the force applicator tip used in the Instron device was 1 mm, and during application of force in the apico-coronal direction, the tip was only in contact with the canal filling material. Due to the conical structure of root canal morphology, the reduction of canal diameter in the apical direction may lead to incorrect results as the applicator contacts the dentin. For this reason, we only obtained sections from the middle and coronal thirds of root canals.

Based on the intra-group comparisons of void spaces obtained in our study, the differences between the void spaces in the coronal, middle and apical thirds of samples filled with AH Plus and MM Seal sealers were found to be significant ($P < 0.05$). In the AH Plus group, the void space in the coronal third was significantly higher than the apical and middle thirds. There was no difference between apical and middle thirds. In the MM Seal group, the void space in the coronal third was significantly greater than the middle third. There was no difference between apical and middle thirds and apical and coronal thirds. However, the largest void space values were detected in the coronal third in the MM Seal and AH Plus groups. There was no statistically significant difference between the void space detected in coronal, middle and apical thirds of EndoSequence BS Sealer and BioRoot RCS groups ($P > 0.05$). However, in the Endosequence BS Sealer group, void spaces in the middle third of the root are greater than in the other regions. The smallest value was determined in the apical third. In the BioRoot RCS group, the largest void space value was determined in the coronal third of the roots. The smallest value was determined in the apical third.

When all the groups were evaluated within themselves, it was found that the void space detected in the coronal third was larger than apical and middle thirds. There was no significant difference in terms of void space between the apical and middle thirds, but the least void space was determined in the apical third. Based on these findings, we can say that canal filling quality in our study was generally superior in the apical third, compared to middle and coronal thirds. This result is attributed to the fact that root canal assumes a circular section in the apical direction, and the narrowing canal supports the adaptation of the main cone (169). Keleş et al. (2014) showed that the least void space was found in the apical third of teeth filled with lateral condensation technique and the largest void space was found in the coronal thirds (145). This finding is consistent with our results.

Based on inter-group evaluation of void spaces, we found that the void space in the MM Seal group was significantly higher in the coronal third of the root compared to Endosequence BC Sealer and BioRoot RCS groups ($P < 0.05$). Furthermore, void space in AH Plus group was significantly higher in the coronal third of the root compared to Endosequence BC Sealer group. No difference was found between the other groups, however, the lowest void space values in the middle and apical thirds of the root were obtained in the AH Plus group. In the middle third, the lowest void space values were observed in the BioRoot RCS group. There was no statistically significant difference in terms of void spaces detected in the entire root ($P > 0.05$), however, the largest void space in the entire root was found in the MM Seal group and the least void space was found in the Endosequence BC Sealer group. Higher void space detected in AH Plus and MM Seal groups compared to bioceramic containing canal sealers can be explained by the assumption that resin-based canal sealers could be exposed to a polymerization shrinkage that could have caused void formation (10, 146). In addition, small particle size (less than 2 mm) and high fluidity of bioceramic-containing canal sealers that can fill the dentin tubules may have resulted in less void formation. Furthermore, the calcium silicate content of bioceramic-containing sealers helps them exhibit little or no shrinkage during hardening (106).

Viapiana et al. (2016) investigated the covering ability of BioRoot RCS and AH Plus sealers in the root canal using three different methods and examined the correlation between them. Extracted premolar teeth used in the study were filled with cold lateral condensation technique. The percentage of cavities in the root canal was assessed by micro-CT, sealing ability was assessed by liquid transport method and dentin adaptation was assessed by fluorescence markers. The bonding of the canal sealer to the dentin was examined using a laser scanning confocal microscope. As a result, significantly more space was detected in the canals filled with BioRoot RCS canal sealer compared to those filled with AH Plus sealer. No difference was found between the canal sealers in the liquid transport method and laser scanning confocal microscopy results. For both materials, bidirectional correlations between the three techniques were close to zero, indicating weak relationships (94). In our study, BioRoot RCS showed less void space in the coronal third of the root compared to AH Plus, whereas it showed more void space in the apical and middle thirds. When the entire root was examined, there was no significant difference between the groups, but BioRoot RCS showed less void space than AH Plus. We can say that our results contradict with Viapiana et al (2016). These differences may be related to the morphological differences of the root canal and the fact that the micro-CT device used in this study is different from the one used in our study and the voltage used is lower. In addition, roots were examined in that study without being separated into apical, middle, and coronal thirds.

Çelikten et al. (2016) evaluated the presence of voids in canal fillings using micro-CT in extracted teeth filled with AH Plus, Endosequence BC Sealer, Smartsealer bio and ActiV GP canal sealers. Void spaces were found in canal fillings made with all root canal sealers. Bioceramic sealers (Endosequence BC Sealer, Smartsealer bio) produced similar void spaces with other groups. The least space was seen in the apical part of the canals (84). The results of this study are consistent with our results.

Pawar et al. (2014) examined leakage in root canals filled with Endosequence BC Sealer, AH Plus and Epiphany root canal filler sealers using a dye penetration method. Horizontal sections were taken from the teeth at apical 2, 4 and 6 mm distances while dye penetration method was performed. Obtained sections were examined with stereomicroscope. Various levels of leakage were found in all experimental groups, but Endosequence BC Sealer and Epiphany canal sealers provided statistically better coverage. Although researchers used a different method from our study as a canal fill assessment method, their results are consistent with our results (148).

Wang et al. (2018) investigated the dentin tubule penetration and canal filling quality of the iRoot SP channel sealer with the same content as Endosequence BC Sealer using stereo microscope and laser scanning confocal microscopy. 40 lower incisors were used. Teeth were filled with iRoot SP and AH Plus sealer using single cone and hot vertical condensation techniques. Horizontal sections were then taken from the teeth at apical 2, 4 and 6 mm distances. Obtained sections were examined with a stereo microscope and a laser scanning confocal microscope and the percentages of void spaces were calculated. It was found that the filling techniques and canal sealers used had no significant effect on void formation. Based on the sections obtained from 2 mm of the apical, it was found that dentin tubule penetration of iRoot SP sealer was significantly higher than AH Plus in both filling techniques. It has was concluded that iRoot SP sealer had better dentin tubule penetration than AH Plus, and could achieve a filling quality similar to that of AH Plus (150).

When the root canal is filled with only canal sealer, a single surface is formed, whereas when filled with gutta-percha and canal sealer, two different surfaces form between the dentin-canal sealer and main cone-canal sealer. Since root canals are not filled only with canal sealer in root canal treatment, we evaluated dentin bonding strengths of fillings performed with combined use of canal sealer and gutta-percha to better reflect clinical conditions. Oliveira et al. (2016) expanded the root canals of extracted teeth using Gates Glidden burs at the middle third zone and sent canal filling materials to the canals with the help of lentulo. They studied the bonding strength of MTA Fillapex (Angelus, Londrina, Brazil), iRoot SP (Innovative BioCeramix Inc. Vancouver, Canada), which has the same content as the Endosequence BC Sealer, and AH Plus canal sealers to root canal dentin walls using push-out tests. They obtained 1 mm thick sections and measured bonding strengths. MTA Fillapex and iRoot SP showed lower bonding to dentin (74). In our study, Endosequence BC Sealer showed higher bonding than AH Plus, therefore we can say that the results of this study are contradict without results. Different results could be due to the fact that canals were only filled with canal sealer in the study of Oliveira et al. (2016).

The quality of the root canal fill and the success rate of endodontic treatment are largely attributed to the covering ability of the root canal sealer (170). Zhang et al. (2009) compared the apical covering ability of iRoot SP (with similar content as Endosequence BC Sealer) and AH Plus root canal sealer using liquid filtration technique. There was no significant difference in apical leakage between bioceramic-containing sealer and AH Plus at 24 hours, 1, 4 and 8 weeks. As a result, iRoot SP canal sealer showed similar apical coverage with AH Plus (171). In our study, no statistical difference was found between AH plus and Endosequence BC Sealer sealer, which is a bioceramic-containing sealer, in terms of bonding to root dentin. Therefore, we can conclude that our results are consistent with Zhang et al. (2009). This is because theoretically, a high bonding of root canal sealer to the dentin provides better coverage (12).

Fisher et al. (2007) reported that open epoxy rings of AH Plus sealer forming strong covalent bonds with the amino groups in the collage network enabled AH Plus sealer to show strong bonding to root dentin (172).

Shokouhinejad et al. (2013) reported that Endosequence BC Sealer exhibited hydrophilic properties and could easily diffuse into dentin tubules due to its small particle structure. Furthermore, Endosequence BC Sealer Sealer hardens by reacting with moisture. During the hardening reaction, it forms hydroxyapatite and binds chemically to tooth structure and gutta-percha, resulting in a 2% expansion after the hardening reaction and thus better bonding to root dentin (173). Bioceramic canal sealers include alumina, zirconia, bioactive glass, glass ceramic, hydroxyapatite and calcium phosphates (174). The alkaline structure of bioceramics has been reported to denature collagen fibers, which makes it easier for canal sealers to attach to dentin tubules (175). However, AH Plus canal sealer is inherently acidic and this may limit its bonding to dentin tubules. Furthermore, the polymer found in AH Plus and MM Seal sealers can cause polymerization shrinkage and disruptions and fractures in the canal. For this reason, bioceramic-containing canal sealers are likely to demonstrate superior sealing properties than resin-containing sealers (86). In our study, we think that the higher dentin bonding strength and least void space found in bioceramic-containing sealers may be related to these properties.

Madhuri et al. (2016) investigated root dentin bonding strength of different canal sealers using push-out bond strength test. They obtained 2 mm sections from extracted teeth filled with single cone technique in. Endosequence BC Sealer group showed significantly higher bonding to dentin than MM Seal group (79). We can say that this result is consistent with the results of our study.

Shokouhinejad et al. (2013) compared the push-out bond strengths of AH Plus and Endosequence BC Sealer sealers in the presence and absence of the smear layer. In Groups 1 and 3, the root irrigation of the root canals was performed with 5.25% NaOCI solution, whereas in Groups 2 and 4, the smear layer was removed with 5.25% NaOCl followed by 17% EDTA. In Groups 1 and 2, the canals were filled with gutta-percha and AH Plus sealer. In Groups 3 and 4, the canals were filled with gutta-percha and Endosequence BC Sealer. There was no statistically significant difference in bonding strength between groups filled with AH Plus and Endosequence BC Sealer. The presence or absence of the smear layer did not have a significant effect on the bonding strength of the canal sealer (83). We can say that the results obtained in this study are consistent with our results.

6. CONCLUSION

This study was planned in two parts. The first part consisted of the comparison of void space presence in the canals filled with AH Plus, MM Seal, Endosequence BC Sealer and BioRoot RCS using micro-CT, and the second part consisted of the evaluation of dentin bonding strengths of canal sealers with push-out tests. The following results were obtained by this study:

1. Micro-CT analysis revealed void spaces in canal fillings in all groups and samples at varying percentages. Therefore, we concluded that none of the root canal sealers were able to provide a void-free canal filling.

2. When the groups were evaluated within themselves, it was found that void spaces detected in the coronal third was significantly higher than apical and middle thirds. Although there was no statistical difference between apical and middle thirds, least void space was detected in the apical third.

3. It was found that MM Seal sealer had the most void space among the canal sealers evaluated in this study. MM Seal group showed significantly more void space in the coronal third than Endosequence BC Sealer and BioRoot RCS groups. AH Plus group showed significantly more void space in the coronal third than Endosequence BC Sealer group. Although no statistical difference was observed between the other groups, the lowest void space values in the middle and apical thirds were obtained in the AH Plus group. In the coronal section of the root, the lowest void space value was obtained in the Endosequence BC Sealer group. No difference was found between the groups in terms of total void space in the entire root, however, the highest void space value was obtained in the MM Seal group whereas the lowest value was obtained in the Endosequence BC sealer group.

4. In terms of bond strength values, MM Seal group showed the least bonding strength value, and the difference was statistically significant.

5. There was no statistically significant difference between the bonding strength values of AH Plus, Endosequence BC Sealer and BioRoot RCS root canal sealers.

6. We think that the newly developed sealers, Endosequence BC Sealer and BioRoot RCS canal filling sealers, can be used as an alternative to AH Plus, which is currently used as a clinical standard.

7. Good dentin bonding of canal sealers can be effective in protecting the integrity of the root canal filling against forces that may cause it to detach during post application or renewal of coronal restoration. Knowing the adhesive properties of sealers in clinical use may influence the prognosis of canal treatment. For this reason, we think that canal sealer selection should be done according to the adhesive features.

8. In our study, a weak negative correlation was found between the bonding strength values of the sealers and the void space values in the coronal third. This result indicates that while the dentin bonding of the canal sealer is increased, the volume of void spaces in the coronal third is reduced to a weaker extent.

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MARMARA ÜNİVERSİTESİ
Diş Hekimliği Fakültesi
Klinik Araştırmalar Etik Kurulu

Projenin Adı: Biyoseramik ve rezin esaslı kanal dolgu patları kullanılarak yapılan kanal dolgularının kalitesinin ve patların bağlanma dayanımının karşılaştırılması.
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Onay tarihi ve sayısı:27.11.2017, 2017-139

Sayın Doç.Dr.Meriç Karapınar KAZANDAĞ

2017-145 Protokol nolu "Biyoseramik ve rezin esaslı kanal dolgu patları kullanılarak yapılan kanal dolgularının kalitesinin ve patların bağlanma dayanımının karşılaştırılması" isimli invitro çalışmanız Marmara Üniversitesi Klinik araştırmalar Etik kurulu tarafından incelenmiş ve etik yönden uygunluğuna karar verilmiştir.

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