ALAA ALMASHHARAWI

CANAL TRANSPORTATION AND VOLUMETRIC DENTIN REMOVAL ABILITIES OF NI-TI ROTARY FILE SYSTEMS IN CURVED PRIMARY ROOT CANALS: CBCT STUDY

PhD THESIS

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Approval

We certify that we have read the thesis submitted by Alaa ALMASHHARAWI titled **"Canal Transportation and Volumetric Dentin Removal Abilities of Ni-Ti Rotary File Systems in Curved Primary Root Canals: CBCT Study"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of PhD of Pediatric Dentistry.

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Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Alaa ALMASHHARAWI

25/12/2021

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Alaa ALMASHHARAWI

Abstract

Canal Transportation and Volumetric Dentin Removal Abilities of Ni-Ti Rotary File Systems in Curved Primary Root Canals: CBCT Study

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Current improvements in nickel-titanium (Ni-Ti) rotary file systems have created a paradigm shift in the root canal therapy of primary teeth. Therefore, it is necessary to perform a comprehensive evaluation regarding the efficiencies of newly manufactured instruments for different parameters. The current study was conducted to evaluate the abilities of RaceEvo, R-Motion, ProTaper Gold (PTG) systems in curved primary root canals with regard to the patterns of canal transportation and volumetric dentin removal by using cone-beam computed tomography (CBCT). Two experimental sets were designed following the determination of experimental groups by using pre- and post-operative CBCT data: canal transportation and volumetric dentin removal. The highest amount of canal transportation was significantly detected in the PTG group in comparison to RaceEvo and R-Motion groups. When the mean values of volumetric dentin removal data were analyzed across all groups, the PTG group again exhibited the significantly highest value of dentin removal volumetrically, compared to RaceEvo, R-Motion and manual instrumentation groups. It is possible to state that R-Motion and RaceEvo rotary systems could be used as reliable alternatives without causing adverse mechanical effects and maintaining the original root canal anatomy of curved primary root canal systems compared with PTG rotary systems and manual instrumentation, with a high diagnostic sensitivity of CBCT in pediatric endodontics when the alternative methods are not adequate.

Keywords: canal transportation; volumetric dentin removal; RaceEvo; R-motion; ProTaper Gold

Table of Contents

List of Tables / Figures

Page

List of Abbreviations

CBCT: Cone Beam Computed Tomography

CHX: Chlorhexidine

CM: Controlled Memory

CT: Computed Tomography

DPC: Direct Pulp Cupping

ECC: Early Childhood Caries

EDTA: Etilenediamine Tetra-asetic Acid

FDI: Federation Dentaire Internationale

FOV: Field of View

GVs: Grayscale Values

HUs: Hounsfield Units

IDC: Indirect Pulp Capping

ISO: International Standard Organization

MPRCF: Mixed Primary Root Canal Filling

NaOCl: Sodium Hypochlorite

Ni-Ti: Nickel Titanium

PTG: ProTaper Gold

RCS: Root Canal System

ROI: Region of Interest

ZOE: Zinc Oxide Eugenol

CHAPTER I

Introduction

There is a great importance for primary teeth on the child's life. This importance lies in being the primary responsible for chewing, phonation, and occlusion functions. The importance of primary teeth is not limited to this matter only it additionally takes part during times of development and improvement of the height of the dental jaws, in breathing and esthetics harmony. Therefore, it is necessary to preserve primary dentition and keep it healthy in the mouth until normal time of shedding (Lopez, et al., 2016). Basically, issues as swelling and pain in the primary teeth could make children feel uncomfortable during their daily life, also, may even influence the presence of the child. Children's dental health is influenced by teaching, ideas, and knowledge on their families. As long as parents are primarily responsible for their children, they should have adequate information about the oral health and care of primary teeth. Specifically, the more certain the mother's behaviour towards dental care, the better the oral cleanliness of the child (Vittoba & Srinivasan, 2016).

Premature loss of primary teeth is viewed as a significant issue in oral health. One of the most frequently recognized results of early loss of teeth in primary dentition is absence of adequate gap in permanent dentition, crowded teeth, eruption problems in the permanent tooth, and midline discrepancy. Additionally, premature loss of primary teeth could negatively influence the life quality of child, eating, aesthetics, speech development, and arch integrity. There might be problems in communicating during pronouncing the words. Likewise, premature loss of primary front teeth it may result problems in the eruption and appearance of permanent teeth. The most common reasons that lead to premature loss of primary teeth are tooth decay, dental trauma, early root resorption and periodontal diseases (Ahamed, et al., 2012; Al Meedani, et al., 2020; Holan & Needleman, 2014; McDonald, et al., 2011; Nadelman, et al., 2020). Premature loss of anterior primary teeth usually is observed more in the maxilla than in the mandible while premature of primary molar teeth is more prominent in the lower jaw. The main cause of premature loss of primary teeth is early childhood caries (ECC) (Ahamed, et al., 2012; Leite Cavalcanti, et al., 2008; Law, 2013).

Tooth decay is quite possibly the most broad youth oral illnesses on the planet (Mathur & Dhillon, 2018). Dental caries (tooth decay) is a huge medical issue around the world. It influences by far most of grown-ups as well as youngsters, from 60% to 90% of them. Severe tooth decay in children is related with poor health, underweight, moodiness, possibility of hospitalization, interrupted sleeping and decrease mental capacity (McGrath, et al., 2004; Sheiham, 2006). Another negative effect should also take into consideration is how oral health affects a child's academic level, the bad oral hygiene the child has, the more the chance the child will not attend to school as a result of toothache and dental abscess. Skipping school because of dental pain or oral disease adversely influences children' s school achievement. These discoveries recommend that improving children's dental hygiene play a role in upgrading their academic knowledge (Jackson, et al., 2011). Especially, considering to determine whether the pulp is healthy or inflamed or at which stage of inflammation the pulp one of the most important success points of the operation because in determining this, the clinician will be able to choose the appropriate treatment. Generally, there are several ways are recommended for treatment primary teeth. They can be categorized into two groups: conservative (the treatment that aims to maintain the pulp vital) and radicular (consisting of root canal debridement and filling the entire root canal). Despite of pulpotomy procedure aims to cast out the pulp tissue from the pulp cavity it is still considered a conservative treatment since its purpose is to leave the radicular pulp vital (Fuks, et al., 2010). In case of pulp injures because of trauma or dental caries could threat the vitality of the tooth, so proper therapy, for instance "Direct Pulp Capping (DPC)", "Indirect Pulp Capping (IPC)" and "Root Canal Treatment (pulpotomy)" should be taken into consideration (Coll, et al., 2017). DPC is performed for primary teeth when pulp exposure occurs by accident in a health pulp during deep dental caries removal procedure or trauma, and the exposure site should not be larger than pinpoint in diameter and the oral cavity should be free of contamination. Pulpotomy is still the most popular therapy in cases of pulp exposure occurs during caries removal in primary molars tooth that free from symptoms (Frencken, et al., 2012). On the other hand, root canal treatment (pulpectomy) is regularly applied to the teeth with necrotic pulp or irreversible pulpitis which are still in restorable condition (Ahmed, et al., 2018; Smail-Faugeron, et al., 2018). The aim of this operation is to maintain the primary teeth in a practical situation and in a healthy condition up to normal shedding time, to avoid toothache, inflammation and premature loss of primary tooth (AAPD, 2016; Ahmed, et al., 2018).

The challenge that may face the clinician during root canal treatment in primary dentition is that primary teeth have unique root morphology. Providing an effective treatment of primary teeth knowing the morphology of primary teeth and the differences that exist within it should be comprehensive by the clinician (Ash & Nelson, 2010). The anatomical features of deciduous teeth should be thought of when arranging and choosing on debridement of the entire root canal especially for the molar ones, which have smaller and more bended root, slighter dentinal walls and a ribbon-shaped root canal morphology (Ahmed, 2013; Fumes, et al., 2014; Pinheiro, et al., 2012). Additionally, the interradicular septa lesion should be taken into consideration in infected primary molars which could be happen anyplace along the root particularly in the furcation area (Ahmed, 2013; Kramer, et al., 2003). Because of these characteristics an appropriate ideal instrument must be chosen which can keep the original shape of root canal without any differences and minimally removed dentin following the instrumentation.

CHAPTER II

General Information

The Importance of Healthy Primary Dentition and Endodontic Treatments

Today, despite the developments in preventive dentistry and the importance of preserving the natural dentition, there are cases where the vitality of the pulp is endangered as a result of dental caries, traumatic injuries or restorative dental treatments and early loss of these teeth is quite common (Alaçam, 2012; Fuks, 2000; Koshy & Love, 2004). Therefore, procedures aimed at the prevention and treatment of pulpal diseases form an essential part of modern dental practice (Waterhouse & Whitworth, 2016).

The main purpose of pulp treatments applied in primary and permanent teeth in children is the maintainance of healthy teeth and support tissues (Koshy & Love, 2004). Early loss of primary teeth may create temporary or permanent aesthetic, phonetic and functional problems such as reduction in arch size, space constriction, perplexity, impacted permanent teeth or ectopic eruption, abnormal language habits and malocclusions (Alaçam, 2012; Fuks, 2000; Waterhouse & Whitworth, 2016). For these reasons, preventing malocclusions that may occur with applied endodontic treatments and protecting the arch size are among the main objectives of pediatric dentistry (Waterhouse & Whitworth, 2016).

Necessity and Success Rate of Root Canal Treatment for Primary Teeth

Differences in crown-root anatomy and pulp physiology of primary and permanent teeth reveal the necessity of evaluating endodontic approaches in children separately from adults (Alaçam, 2012).

Pulp treatments applied in deciduous teeth are examined under two main headings (Dammaschke, et al., 2019; Fuks, 2000).

1- Vital Pulp Treatments: Primary tooth decay, less frequently trauma or to maintain pulp vitality in teeth affected by different reasons are aimed treatment approaches. IPC, DPC and partial or full pulpotomy treatments are considered as vital pulp therapies.
2- Radical Pulp Treatments: Root canal treatment and root filling is a treatment approach that includes.

In cases of irreversible pulpitis due to dental caries or trauma root canal treatment procedure is mandatory since the purpose of this treatment is to keep the primary tooth without losing the main function of the tooth (Fuks, 2000).

The behavioral problems seen in pediatric patients, in addition to the difficulties that encounter the clinicians during root canal preparation because of the complex primary root canal morphology, instrumentation, medication and filling materials are the concern that it may damage the permanent tooth germ, will not encourage the clinicians to make root canal treatment. Despite these problems, the success rate achieved in root canal treatment makes doctors resort to this type of operations (Fuks, 2000).

Extraction the pulpally infected primary teeth and placing a space maintainer application can be an alternative treatment procedure to root canal treatment in pediatric dentistry. However, in cases where adequate follow-up cannot be made and oral hygiene cannot be provided, tooth decay, gingival inflammation, and like the early loss of the space maintainer all these kinds of problems may be encounter the clinicians.

The criteria that used in the treatments of permanent root canal is the same criteria that used to evaluate the success of endodontic treatment in primary teeth. The primary tooth treated should be able to remain in function without pain and signs and symptoms of infection. Primary tooth roots should resorb normally with no adverse effect on the formation of permanent teeth germs (Waterhouse & Whitworth, 2016).

Indications and contraindications of root canal treatment of primary tooth (Jena, 2020):

Indications:

1- Patients, as well as their parents, should be cooperative.
2- It is preferable to have a patient who is in good health and does not have any serious illnesses.
3- It is indicated signs of primary teeth in the absence of permanent successor teeth.
4- Irreversible pulpitis
5- Internal resorption
6- It is expected that at least 2/3 of the root length will be accessible.
7- At least 2/3 of the root length is supposed to be reachable.

Contraindications:

1- A mobile tooth or a lack of bone support.
2- A tooth that cannot be resorbed.
3- Any dentigerous or follicular cysts that may be present beneath the surface.
4- The remaining root length is less than two-thirds of its original length.
5- In cases of pulpal floor has been perforated.
6- Children who have a medical condition.

In cases where existing infection cannot be controlled with vital or non-vital endodontic treatments and bone support cannot be restored, tooth extraction should be considered (Fuks, 2000; Holan, et al., 1992).

Histological and Morphological Variations Between Primary and Permanent Teeth

In order for a successful pulpal treatment in primary and permanent dentition, clinicians need to be aware of the continuous morphological changes of primary teeth and the anatomical variations of both types of dentition (Goerig & Camp, 1983; Muller-Bolla, et al., 2021).

Histological structure of pulp in primary teeth, when compared the odontoblast morphology, weil and cell-rich layer, vascularization, connective tissue fibers, pulp mineralization and predentin layer of deciduous tooth pulp with permanent teeth, there were no structural variations among the pulpal tissues of primary and immature teeth. The only difference was observed in the peripheral coronal pulp and pulp horns as dense zone of cap like collagenous and reticular fibers network in primary dentition (Fox & Heeley, 1980; Nelson, 2019).

It is known that primary teeth are less sensitive to painful stimuli than permanent teeth due to the difference in the number and distribution of neural elements (Khademi, et al., 2021; Rapp Ra & Strachan, 1967). It has been reported that with the onset of resorption in primary teeth, degenerative neural changes began to be observed first (Khademi, et al., 2021; Mohuiddin, 1950). The main nerve fiber bundles in the apex of decidious and permanent teeth are seen along the axial pulp and the peripheral nerve fiber bundles branch out as they approach the cervical region of the pulp, progress more peripherally and partially reach the odontoblast layer. Furthermore, the number of nerve fibers in primary teeth both in the subodontoblastic nerve plexus and in the marginal nerve plexus are less than in the permanent teeth (Khademi, et al., 2021). The dentin of the primary tooth is in the form of two layers, prenatal and postnatal. Primary teeth have 2-4 times thicker peritubular dentin than in permanent (Hirayama, et al., 1986; Khademi, et al., 2021). On the other hand, tubule diameters in primary tooth dentin are larger than permanent teeth and close to the pulp (Sumikawa, et al., 1999).

The mineral content of permanent and primary tooth dentins differs as well. The mineral concentration of permanent dentin is higher than that of primary dentin, which is less hard and less mineralized than that of permanent (Angker, et al., 2003; Hosoya, et al., 2000; Rontani, et al., 2000).

Development of the root begins when enamel and dentin formation reach the enamel-cementum junction. Hertwig's epithelial root sheath created by the epithelial dental organ initiates root development and root shaping. Along the root development, the apices are widely open, covered by the epithelial diaphragm, and the dentinal walls are apically diverged. At this stage, each root consists of a single canal. When the root of the tooth reaches the required length, the epithelial sheath fades away, but the deposition of dentin in the root canal proceeds (Waterhouse & Whitworth, 2016). Deciduous tooth roots begin to resorb immediately after their formation is complete. Due to this resorption process, the apical foramen location is constantly changing. Secondary dentin deposition within the canal has affect on changes in the number/size of root canals, variations, and the formation of many small attachment areas among the lingual and facial sides of the root (Goerig & Camp, 1983; Waterhouse & Whitworth, 2016). It should be considered that these variations, which occur in the permanent and primary root canals, cannot be observed on radiographs since they are mostly in the faciolingual plane.

Physiological root resorption in decidious incisors and canine teeth initiates from the lingual surface of apical region due to the position of the germ in permanent dentition, whereever, in deciduous molars, it starts from the inner side of the root close to the inter-radicular septum. As the resorption continues, the apical foramen begins to position more coronally than the anatomical apex of the root this makes it difficult to determine the root canal length radiographically. The resorption may extend along the root and into the root canal and form different connections with the periapical tissues except for the apical foramina, lateral and accessory canals. For this reason, it is stated that the use of electronic apex locator is not suitable for determining the root canal length in primary teeth (Waterhouse & Whitworth, 2016).

For a successful root canal treatment, the shape of the root, its number, the morphology and variations of the root canal, as well as the accessory canals that may exist should be considered (Waterhouse & Whitworth, 2016).

According to Nelson and Ash, the main differences between the pulp chambers and root canals of primary and permanent teeth are as follows:

1. Primary teeth are smaller in all sizes than the permanent teeth that will replace them.
2. Primary tooth crowns are mesiodistally wider than permanent teeth relative to the length of the crown.
3. Primary tooth roots are narrower and longer than permanent teeth in proportion to the length and width of the crown.
4. The cervical 1/3 level on the facial and lingual surfaces of anterior primary tooth crowns is more prominent than permanent teeth.
5. Primary teeth are narrower at the enamel-dentin border than permanent teeth.
6. In primary molars, the facial and lingual surfaces converge occlusally, and the occlusal surface is narrower in the fasciolingual direction compared to the width in the cervical region.
7. The roots of primary molars are proportionally thinner and longer than the roots of permanent molars.
8. The roots of primary molars extend from the cervical region.
9. The enamel in primary teeth is thinner (approximately 1mm) than in permanent teeth.
10. Dentin thickness between the pulp chamber and enamel is less in primary teeth than in permanent teeth.
11. The pulp chamber in primary teeth is larger than in permanent teeth.
12. In primary teeth, pulp horns are wider than permanent teeth and are closer to the surface (Nelson & Ash, 2010).

Root Canal Anatomy in Primary Teeth

Upper and Lower Incisors

Root canal morphology in anterior primary teeth is similar to the shape and form of the tooth root. The root canals of the upper deciduous teeth are approximately round, but slightly narrower faciolingually. Generally, these teeth are single-canal. Although apical ramifications, accessory and lateral canals are not common, they can be seen (Waterhouse & Whitworth, 2016). The lower primary incisors may have a single, conical and wide canal or may end up as 2 canals in the apical region (Cleghorn, et al., 2010; Nelson & Ash, 2010; Waterhouse & Whitworth, 2016). The probability of finding the second canal is less than 10%. The presence of lateral and accessory canals is uncommon (Waterhouse & Whitworth, 2016). The simple root canal system of the primary anterior teeth makes the treatment of these teeth easier (Goerig & Camp, 1983).

Upper and Lower Canines

Upper and lower canines have the simplest root canal system among primary teeth. Primary canines have a single, wide, rounded triangular root canal with the base on the facial surface compatible with the external morphology of the tooth root (Cleghorn, et al., 2010; Waterhouse & Whitworth, 2016). Bifurcation is not seen in the canals under normal conditions, and lateral and accessory canals are rare (Waterhouse & Whitworth, 2016).

Upper and Lower Primary Molars

Upper deciduous molars have 3 roots, 2 buccal and 1 palatal, while lower deciduous molars have a total of 2 roots, mesial and distal. The roots of deciduous teeth are thinner and longer than the length and width of the crown. It is also more divergent to allow the formation of permanent tooth germ (Waterhouse & Whitworth, 2016).

Morphological variations in root canals are most common in the mesial root of upper and lower primary molars. This variation begins with a narrow isthmus thinning in the apical region, between the lingual and buccal boundaries of the apical pulp canal. As a result of the continuation of the secondary dentin deposition, two or more separate root canal formation can be observed. Many fine connecting branches and lateral fibrillary interconnecting branches form a network of connections between the facial and lingual surfaces of the root canal. The root canals' facial and lingual surfaces are connected by a network of fine connecting branches and lateral fibrils roots. These variations in the mesial root are less common than in the distal and lingual root (Waterhouse & Whitworth, 2016). Accessory canals, lateral canals, and apical branching in the pulp are quite common and are seen in approximately 10-20% (Goerig & Camp, 1983; Waterhouse & Whitworth, 2016).

Upper First Primary Molar. : Upper first primary molars usually have 2-4 root canals in accordance with the morphology of the root. The palatal root is usually round and longer than the other two buccal roots (Waterhouse & Whitworth, 2016). In comparison to the other three roots, the distobuccal root is the shortest and has the smallest diameter root canal (Cleghorn, et al., 2010; Nelson & Ash, 2010). The fusion of the palatal and distobuccal roots is observed in approximately 1/3 of the upper first primary molars (Waterhouse & Whitworth, 2016). Despite the possibility of 2 canals in the mesiobuccal and distobuccal roots, each of the mesiobuccal, distobuccal, and palatinal roots usually has a single canal. Even if there is fusion in the distobuccal and palatal roots, the 3-canals form is the most common configuration (Aminabadi, et al., 2008; Bagherian, et al., 2010; Zoremchhingi, et al., 2005). The possibility of two canals in the mesiobuccal root is common and its frequency has been reported to be approximately 75% (Waterhouse & Whitworth, 2016).

Upper Second Primary Molar. : Although there are usually 3 separate roots in the upper second primary molars, there is fusion between palatinal and distobuccal roots in some teeth (Bagherian, et al., 2010; Zoremchhingi, et al., 2005). The palatal root is the longest root and the distobuccal root is the shortest and rounded root (Cleghorn, et al., 2010). The Upper second primary molars have approximately 2-5 canals according to their root shape. The canal at the mesiobuccal root often bifurcates or, in some cases, may progress as two separate canals. About 85 % to 95 % of maxillary second primary molars have this condition (Waterhouse & Whitworth, 2016). In fusion roots, there may be a single, common canal, 2 separate canals, or 2 canals connected by a narrow isthmus (Waterhouse & Whitworth, 2016).

Lower First Primary Molar. : In mandibular first primary molars, the incidence of having two canals in the mesial root and one canal in the distal root is generally higher in accordance with the anatomy of the external root of the tooth (Cleghorn, et al., 2010; Waterhouse & Whitworth, 2016). Many studies indicate that there may be one or two canals in both the distal and mesial roots of mandibular first molars (Aminabadi, et al., 2008; Bagherian, et al., 2010). While 75% of the mesiobuccal root has two canals, it has been reported that 25% of the distal root can have more than one canal (Waterhouse & Whitworth, 2016).

Lower Second Primary Molar. : Although there are usually three canals in the lower second primary molars, 2-5 canals can also be observed. There are usually 2 canals in the mesial root (Cleghorn, et al., 2010). While 75% of the mesial root has 2 canals, it has been reported that 25% of the distal root can have more than one canal (Hibbard & Ireland, 1957; Waterhouse & Whitworth, 2016).

Root Canal Treatment Application Stages in Primary and Permanent Teeth

The same procedure is followed during root canal treatment in primary and permanent teeth. Generally, under local anesthesia and rubber cover isolation, the caries is removed and the pulp chamber is opened. Root canal treatment in primary teeth can be done in a single visit (Gutmann, 2011).

Root Canal Treatment Access Cavity Preparation and Debridement

Introduction to the complex root canal system is one of the first and most important steps in root canal treatment (Gutmann, 2011). The preparation of the access cavity in primary and permanent teeth is based on the same basic principles (Waterhouse & Whitworth, 2016). Objectives of the access cavity preparation (Gutmann, 2016):

1- Removing all existing carious tissue.

2- Protecting healthy tooth tissue.

3- Completely removing the roof of the pulp chamber.

4- Removing all necrotic or vital coronal pulp tissue.

5- Localizing all canal openings.

6- Providing straight or direct access to the canals.

A properly prepared access cavity should provide a direct and straight access path to the canal system. Straight inlet path provides effective debridement of the entire canal cavity and reduces the risk of instrument breakage (Gutmann, 2016; Mannan, et al., 2001).

When opening the access cavity, important differences such as crown length between permanent and primary teeth, shape of the crown, thin dentin walls at the pulpal base and roots should not be forgotten. In primary molars, care should be taken in terms of the risk of perforation, since the distance required to enter the pulp chamber from the occlusal surface and the distance to the pulpal base is less than that of permanent teeth. When the pulp chamber is reached, the entire ceiling should be removed. At the same time, since primary tooth crowns are more bullous than permanent teeth, it is sufficient to expand the cavity less towards the outer corners of the tooth to reach the canal openings (Waterhouse & Whitworth, 2016).

The roots of the primary teeth are curved to allow the development of the permanent tooth underneath. This curvature increases the risk of perforation in the apical region and coronal 1/3 of the root during instrumentation (Waterhouse & Whitworth, 2016).

Cleaning and Shaping the Root Canal System

After the preparation of the coronal access cavity, root canal preparation can be started.

Main purposes of cleaning and shaping root canals (Peters, et al., 2016):

1. Removal of hard and soft infected tissues.
2. To ensure that the irrigation solutions reach the apical canal space.
3. To provide space for the medicament or canal filling material to be used.
4. It can be listed as maintaining the integrity of the root structure.

Factors affecting the cleaning and shaping of root canals (Wildey, et al., 1992):

1. Structure of the cut dentin tissue
2. Anatomical configuration of root canals
3. The material from which the canal instrument is made (stainless steel or nickel titanium)
4. Design of the canal instrument
5. Indicated as the solutions used during the process.

The first working length is determined according to the radiograph taken with the parallel technique, and then local anesthesia and rubber cover isolation are provided.

The exact working length is determined as a result of the radiograph taken with the files placed in the canals. It has been stated that the use of electronic apex locator in determining the working length in primary teeth is not reliable due to root resorption. In the literature, there are some studies indicating that apex determining systems can be used in determining the length of the canal in primary teeth and can be an alternative to radiographic examinations (Kielbassa, et al., 2003; Saritha, et al., 2012).

The ideal working length should be 1-2 mm shorter than the radiographic apex (Goerig & Camp, 1983). If the tooth has signs of apical root resorption, it is recommended to work 2-3 mm shorter than the radiographic length in order to preserve the periapical tissues (Garcia-Godoy, 1987; Waterhouse & Whitworth, 2016).

After determining the working length, the channels are cleaned and shaped. The canals can be enlarged up to file 30-35 by increasing a few lengths over the first file that fits into the canal (Waterhouse & Whitworth, 2016).

Basic cleaning and shaping strategies for root canal preparation can be classified as crown-down, step-back, apical expansion, and hybrid techniques. In a crown-down approach, the clinician passively inserts the oversized canal instrument into the canal to a depth that allows easy advancement. In the next step, a smaller canal file is used to drive deeper into the canal. The third instrument is inserted deeper as before, and this process continues until the apical termination is reached. Both hand tools and rotary tools can be used with the crown down technique (Peters, et al., 2016).

In the step-back approach, the length of the working length gradually decreases as the size of the instrument increases. Thus, less flexible instruments are prevented from forming steps at the apical curvature, while a taper is created in the coronal region for occlusion (Peters, et al., 2016).

In the standardized technique, the working length is considered the same for each instrument used to shape the root canal. For this reason, the shape of the file used gives the canal its final shape (Peters, et al., 2016).

Nowadays, many rotary file techniques use the crown down technique to minimize torsional loads, thus reducing the risk of instrument breakage (Peters, et al., 2016). All the basic techniques described to date can be combined with a hybrid technique to compensate or reduce the shortcomings of each instrument (Peters, et al., 2016).

The use of sonic and ultrasonic instruments is not recommended in primary teeth due to thin root walls, and it is considered that the use of instruments such as Gates Gliden or Peeso drill is contraindicated due to the risk of perforation (Waterhouse & Whitworth, 2016). Seow et al, stated that ultrasonic instruments can also be used in primary tooth canals (Seow, 1991). The use of NiTi instruments is recommended in primary tooth root canal treatment and it is stated that conventional and rotary file techniques are ideal for primary teeth (Waterhouse & Whitworth, 2016). In cases where stainless steel files are used during treatment, precurving the file in accordance with the canal curvature helps the file to follow the canal path, thus preventing perforation (Goerig & Camp, 1983; Waterhouse & Whitworth, 2016).

Principles of cleaning and shaping the root canal system. : Disinfection of apical periodontitis and sealing of the canal system are the most important biological targets of root canal therapy. However, there is no complete consensus on how to achieve this goal. Planktonic microorganisms that present in the pulp cavity and the coronal part of the root canal can be killed by irrigation agents applied in the early stage of treatment. However, less accessible areas or bacteria in the biofilm cause the existing apical periodontitis to continue or reoccur. Today, it is thought that these bacteria can only be targeted after mechanical root canal preparation (Peters, et al., 2016).

Mechanical purposes. : The ideal mechanical goal of root canal instrumentation is to mechanically shape all root canal surfaces. However, studies indicate that it is not possible to achieve this goal with existing techniques (Paque, et al., 2009; Peters, et al., 2001).

There should be no preparation errors such as transport, ledge and perforation in canal shaping. Procedural errors have no effect on the desired outcome, however, it has been reported that they create inaccessible areas in the root canal system in terms of infection control (Lin, et al., 2005; Peters, et al., 2016). Another important mechanical goal is to preserve as much cervical and radicular dentin as possible so as not to weaken the tooth tissue, thus preventing a root fracture from occurring. Anatomy studies have shown that the dentin wall thickness is 1 mm or less before root canal shaping (Degerness & Bowles, 2010; Garala, et al., 2003). Although a precise minimal root wall thickness has not been specified, 0.3 mm is considered a critical value by some researchers (Lim & Stock, 1987). Adequate access cavity preparation and optimal expansion of the coronal 1/3 of the root canal should be ensured to avoid over-preparation and perforation (Peters, et al., 2016). Obtaining the desired shape of the root canal is easy in wide and straight canals, but difficult in curved and narrow canals. The use of files numbered 25-30 is recommended for shaping the apical curvature. This is because it is difficult to cross the apical curvature and reach the working length using larger files. Over preparation at the apical one third in curved root can lead to canal transport, other iatrogenic errors such as perforation and ledge are encountered (Martin & Blaskovicg, 1997).

Biological purposes. : Optimal infection control is closely related to preparation, antimicrobial efficacy, removal of infected pulp and dentin, and space for irrigation solution (Peters, et al., 2016).

With traditionally used needles and injectors, the solution moves passively through the canal. With passive needle irrigation, the solution advances only 1mm from the tip of the needle (Gulabivala, et al., 2010). Although enlarged channels and thinner needles allow deeper needle penetration, the entire apical region is difficult to clean, especially in narrow and curved channels (Amato, et al., 2011; Heard & Walton, 1997; Reynolds, et al., 1987; Wu & Wesselink, 1995).

Technical Purposes. : Although a continuous taper including the original shape and curvature of the existing root canal is a desirable goal in shaping the root canal system, the final apical shaping size and taper remains a controversial topic in root canal therapy (Baugh & Wallace, 2005). Some studies indicate that disinfection is better with a wider final apical size (e.g. 50 or more) with a small taper of .02-.05 (2-5%) (Card, et al., 2002; Rollison, et al., 2002). Other studies, on the other hand, argue that there is no difference between whether the final size selected is large or small (Coldero, et al., 2002; Yared & Dagher, 1994).

In the root canal system, disagreement continues between researchers who prefer a smaller apical preparation and conical shape, and those who favor larger preparations that allow the removal of infected dentin and irrigation solutions to reach the apical area. However, the common view of both parties is to preserve the original shape of the canal during preparation. Otherwise, sufficient amount of antimicrobial agent cannot reach the apical 1/3 part of the root canal (Möller, et al., 1981).

Complete disinfection of residual intraadicular bacteria in the apical part of the root canal is very important. A wider apical preparation removes infected dentin, allowing irrigation needle advancement and helping antimicrobial agents penetrate deeper into the root canal (Chow, 1983; Falk & Sedgley, 2005).

It has been reported that rotating NiTi files with 3 different cones, no. 20, 30 and 40, instruments no 20 left more debris in the apical region compared to instruments no 40 (Usman, et al., 2004). On the other hand, using files no. 25 and 40, bacterial growth between both groups after instrumentation was observed no statistically significant difference was observed, and no bacterial growth was observed after 1 week of calcium hydroxide treatment (Yared & Dagher, 1994).

When comparing the Step down technique applied with extra apical expansion up to file #35 and the step back technique applied without apical expansion, it was reported that no significant difference was found between the groups with and without apical expansion in terms of bacterial colony formation. These investigations concluded that there is no need to remove extra dentin in the apical region if a suitable taper is achieved in the coronal region (Coldero, et al., 2002).

Tools Used in Root Canal Preparation

General Characteristics of Instruments Used in Root Canal Preparation

End design. :The tip of the canal instruments used in root canal preparation guides the file and helps the file to penetrate deeper. A clinician unfamiliar with tip design may encounter problems with canal transportation or instrument breakage as a result of excessive torsion force (Peters, et al., 2016). The radius and angle of the leading edge and the distance of the groove from the tip of the tool of the canal instrument determine the cutting ability of the file tip, while the cutting ability of the tool and the hardness of the tool determine the transport tendency of the canal (Peters, et al., 2016). Studies show that tip design affects instrument control, efficiency, and canal shaping outcome (Mize, et al., 1998; Mizutani, et al., 1992). In Nickel-Titanium (NiTi) files used in rotary instrument systems, preparation errors are avoided as much as possible by using a non-round cutting tip (Hülsmann, et al., 2001).

Dimensional and cross-sectional design. : The grooves on the file are responsible about removing the dentin fragments and soft tissue from the canal wall. The effectiveness of grooves depends on their depth, width, configuration and surface finish. The diameter of the canal files increases with every millimeter along the working surface from the file tip to the handle, and this increase is expressed as taper. Canal instruments can have a fixed or variable taper. In canal instruments with larger taper, the tip of the instrument is designed to act as a guide, while the middle and coronal part of the working part of the instrument is designed to contact the canal walls (Peters, et al., 2016).

ISO standards. : Some standard specifications have been established to improve the quality of endodontic instruments (Ingle, 1961). The International Standards Organization (ISO) has worked with the federation dentaire internationale (FDI) to define these specifications, and these standards are indicated by an ISO number (Peters, et al., 2016).

An important feature of hand tools designed to ISO standards is a defined increase in tip diameter of 0.05 or 0.1mm, depending on the size of the tool. Files of type K and Hedström in ISO standards are available in different lengths such as 21, 25, 31mm: However, all have 16mm long cutting edges (Peters, et al., 2016).

According to ISO standards, the cross-section diameter of the first rake angle of a canal tool (the point where the cutter begins) D0, 1mm coronal point D1, The 2mm coronal point of D0 is the D2 point and the D16 point with the largest diameter is the point where the cutting edge ends. Each channel tool gets its numerical number from its diameter at the D0 point, diameter increases by 0.02mm for every 1mm of length and a specific color code is assigned to this tool (Peters, et al., 2016).

Alloy. : There are two main types of alloys for endodontic appliances: stainless steel and nickel-titanium (NiTi). Most hand tools are made of stainless steel and are highly resistant to breakage. Similarly, burs such as Gates Glidden and Peeso Drill used in low-speed hand tools are also made of stainless steel. Instruments designed for root canal preparation in rotary systems are made of nickel titanium. NiTi alloys offer properties such as flexibility and wear resistance (Peters, et al., 2016).

Physical and chemical properties of nickel-titanium and steel alloys. : The alloy, called nitinol, consists of 55% nickel and 45% titanium by weight. Walia et al, thought that the pseudoelastic properties of 55-nitinol could be advantageous in endodontics and hand instruments, and showed that NiTi instrument #15 is 2-3 times more flexible than stainless steel instruments and more resistant to angular deflection. It has been noted that when a NiTi instrument is bent up to 90 degrees, there is no plastic deformation in the grooves of the instrument and the forces required to bend endodontic files up to 45 degrees are reduced by 50% with NiTi (Peters, et al., 2016; Walia, et al., 1988).

It has been stated that these properties of NiTi are the result of molecular crystal phase transformation in the specific crystal structures of the austenitic and martensitic phases of the alloy (Thompson & Dummer, 2000). The external stresses transform the austenitic crystal form of the NiTi alloy into a martensitic crystalline structure that can accommodate more stress without increasing the stress. As a result, a NiTi file is capable of returning to its original shape after being deformed (Peters, et al., 2016). Recent research into the development of NiTi alloys has shown that new NiTi alloys can be up to 5 times more flexible than currently used alloys (Huang, et al., 2008; Shen, et al., 2013).

Canal Files Used in Root Canal Treatment

Type K canal files. : Canal files are instruments that expand the canal with repetitive entering and exiting movements in the apico-coronal direction. In the past, canal instruments were originally made of carbon steel. Afterwards, the stainless steel used in production greatly increased the quality of the tools. Recently, K-files made of Nickel-Titanium have also been introduced (Peters, et al., 2016).

The files were first produced by Kerr Manufacturing Co. Manufactured by the company and named as K-file or K-type reamer. Type K files and type K reamers are produced by rotating the round metal along its long axis, forming partially horizontal cutting blades on it (Peters, et al., 2016). K-reamers are similar in overall design to K-files, but with fewer threads per mm of working surface than K-file (Schafer, 1997).

Type K instruments are useful tools for channel entry and channel expansion. Generally, using only with reaming (rotation) movement causes less transport in the canal compared to their use with filing movement (Glosson, et al., 1995; Song, et al., 2004).

A pre-bevel can be given to K-type files by bending them before they are placed in the canal. It should be noted that this procedure may create extra stress on the file and cause permanent deformations and should be done with care (Seto, et al., 1990).

Type H canal files. : Type H tools, also known as Hedstrom files, are made of round stainless steel. With blades with a positive rake angle and cutting rather than scraping angles, these files are effective in translational movements (Schafer, 1997). It is not recommended to use H files with rotational movements due to the possibility of breakage (Peters, et al., 2016).

Barbed Broach Files. : Barbed Broach files are produced in different sizes and colours. These instruments, with sharp metal spines angled coronally, are designed to remove vital pulp from root canals (Peters, et al., 2016).

Patency Files. : Patency files that provide canal path patency are usually 10 and 15 K-files. These files are small and recommended for use in many rotary instrument systems. A higher clinical success is aimed with patency files used to remove accumulated debris and maintain working length (Ng, et al., 2011).

One of the concerns with a patency file is the possibility of pushing debris out of the foramen instead of a cleaning effect. However, one in vitro study indicated that continuous flushing of channels with sodium hypochlorite (NaOCl) minimized the risk of inoculation (Izu, et al., 2004). There are only initial clinical findings supporting the use of patency files. However, experts have noted that this technique involves relatively few risks and can provide some benefits if used with caution (Peters, et al., 2016).

Endodontic Instruments Working with Low Speed Motor

Gates-Glidden. : Each Gates-Glidden bur has an elongated shank with parallel walls and a short oval cutting head with a reliable tip. They can be produced from stainless steel and NiTi alloy and in the range of 750-1500 rpm can be safely used to expand the coronal portion of the canal (Davis, et al., 2002; Peters, et al., 2016). When used incorrectly, it causes a dramatic reduction in radicular wall thickness (Gluskin, et al., 2001; Isom, et al., 1995). Higher speed, excess pressure, incorrect insertion angle and aggressive use in canals can result in errors such as trip perforation. For this reason, they are recommended to be used only on straight sections of ducts (Peters, et al., 2016).

Peeso drills. : Peeso drills, usually made of stainless steel, are used in root canals, coronal expansion or post preparation. They can be used in low speed tools with a rotation speed of 800-1200 rpm.The cutting head is longer and more parallel compared to Gates-Glides (Peters, et al., 2016).

Current Rotary Tool Systems

Rotary instrument made of stainless steel for root canal preparation systems have been used for more than half a century. Canal transport and instrument fracture are the main problems encountered in these systems. The use of more flexible NiTi alloys in rotary instrument systems in the early 1990s allowed continued instrument rotation, resulting in reductions in canal preparation errors and instrument fractures (Peters, et al., 2016).

The instruments differ according to the alloy used, the design and the cutting action. The various features incorporated into the tool help prevent procedural errors, increase tool effectiveness and canal shaping quality. For instance, the presence of a longer pilot tip or asymmetrical cross-section will keep the tool more centered along the long axis of the channel, while increasing the core diameter of the tool will increase the torsional resistance and reduce the risk of tool breakage (Peters, et al., 2016).

Many variables and physical properties affect the clinical performance of NiTi rotary systems (Kuhn & Jordan, 2002; Peters & Barbakow, 2002; Thompson, 2000). Clinical practice has yielded a great deal of information about NiTi instruments, such as the causes of instrument fracture and the sequencing of instruments (Barbakow & Lutz, 1997; Peters, et al., 2016). NiTi instruments have been shown to significantly reduce the incidence of canal shaping errors, however, it is stated that it can be broken more easily than hand files (Peters, et al., 2016; Pettiette, et al., 2001).

Revo-S rotary files system. : The Revo-S rotary instrument system includes NiTi instruments with 3 asymmetrical cross-sections and an inactive tip. The asymmetrical cross section of the Revo-S facilitates the instrument to penetrate deeper into the canal with a 'snake-like' movement, offers a canal shape compatible with biological and ergonomic requirements and reduces stress on the instrument. It is suggested that this system optimizes root canal cleaning by removing the formed dentin debris. In addition, it offers different options for apical termination that best suits the biological and ecological criteria of the canal (AS30, AS35, AS40) (Revo-S, 2019).

The canal file has three cutting edges (R1, R2, R3) located on three different radians. The smaller section provides more flexibility and better adaptation to the curvature. Extended helical machining up to the coronal region increases the flexibility of the tool. Reducing the contact surface of the blade on the dentin reduces stress (Revo-S, 2019).

Three instruments are defined as SC1, SC2 which are used for root canal cleaning and shaping and as SU which is used for root canal finishing. SC1 cleans debris more effectively due to asymmetrical cross-sections. The SC2 instrument has a symmetrical cross-section and 4% taper allowing better penetration. The existing equilateral section provides excellent guidance to the instrument up to the apical region of the canal, depending on the force balance, and adheres to the canal anatomy in the apical region, preventing zip formation. It prevents the debris from being packed in the apical region and beyond by enabling the debris to be carried upwards. The gradual preparation of the preparation avoids screwing effects. SU plays an important role in softening the root canal walls. Due to its asymmetrical cross-section, it repeats the movement of the first 2 tools so that the conical shape of the channel is preserved. Contributes to canal cleaning by carrying dentin debris upwards (Revo-S, 2019).

One Shape rotary files system. : The One Shape canal file is a file with a variable cross-section through the file and a taper of 6%. Asymmetrical cross-section reduces the risk of stress-induced breakage on the file (Diemer, et al., 2013). Being able to reach the working length enables the canal to form inaccordance with its original shape and curvature.

Having a single file system reduces treatment time (Bürklein, et al., 2013). Turker et al. conducted a study in which different file systems evaluated the amount of bacterial exit from the apical region and it was shown that the One Shape files system caused less bacterial debris moved to the apical region compared to other rotary instruments (Türker, et al., 2015).

Manufacturers apply various thermal treatments to the alloys through which the instruments are made in order to reduce the failure incidence of NiTi files during clinical use, and they focus on increasing the cyclic fatigue resistance of instruments by modifying the design specifications (Gündoğar & Özyürek, 2017; Peters, et al., 2012). One Curve and HyFlex are single file systems that use rotational motion and are manufactured using different heat treatment procedures.

One Curve (OC) rotary files system. : OC is a new-era root canal document, which became currently delivered to the market via way of means of producer and is produced with C-Wire warmth remedy generation. The producer declares that this generation offers 33% faster root canal preparation in comparison to the reciprocating single file structures and as a result the clinicians could have greater time for irrigation.

When as compared to One Shape (OS; Micro Mega, Besancon, France), which is the previous-era single-file gadget of this producer, the cyclic fatigue resistance became pronounced to be 2,4 instances higher (Pedulla, et al., 2016; Yılmaz, et al., 2018).

Hyflex Electro Discharge Machining (EDM). : HEDM, however, works with non-stop rotation movement and is made of managed memory (CM) with the aid of using the usage of the digital discharging machining (EDM) era. This method is based on shaping the report with the aid of using melting and vaporizing the material through the electric discharges. EDM era became suggested to offer the report a crater-like look and an extended resistance to cyclic fatigue (Pedulla, et al., 2016; Yılmaz, et al., 2018).

TruNatomy Rotary System. : Trunatomy (Dentsply Sirona, Ballaigues, Switzerland), another NiTi rotary system, includes 5 types of files. These are designed as #20

(8% taper), #17 (2% taper), #20 (4% taper), #26 (4% taper) and #36 (% taper). Additionally, due to a new heat treatment procedure introduced by the manifacturer, the TruNatomy files have 4 times more elasticity and fracture resistance than other file systems produced with the traditional heat treatment technique (Özyürek, et al., 2018).

VDW Rotate System. : Three files with #15 (4% taper), #20 (5% taper) and #25 (4% taper) are consisted in the VDW Rotate (VDW, Munich, Germany) system. The cross sectional files are designed as S-shaped and off-center with the constant taper which are developed to be used with a special heat treatment by the manufacturer (Özyürek, et al., 2018).

RaceEvo Rotary System. : The RaceEvo (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) system was recently introduced on the market. The files have cross-sectional shaped design and cutting blades which decrease the risk of screw effect and help the instrument to move controlled in the root canal (Schafer & Vlassis, 2004). These files are NiTi alloys that are operated by exposing to heat in order to increasing their elasticity and reduce the risk of fracture (Shen, et al., 2013). The system has numerious file sizes such as; #15/4%, #25/4%, #25/6%, #30/4%, #30/6%, #35/6%, #40/4% and #50/4%. Each package includes one glide path and two shaping files which the sizes can be chosen according to user's therapeutic approach. Speed range recommended by the manufacturer is 800-1000 Rpm with continuous rotational motion and 1,5 Ncm torque (RaceEvo, 2019).

R-Motion Rotary System. : This system is also recently produced on the market similar to RaceEvo. R-Motion reciprocating instruments have some advantages such as; high elasticity with heat-treatment process, resistance to cyclic fracture, simple use with all-inclusive rotary and shaping tool and minimally invasive in the root canal with small tapers. The users can only operate the #15/4% (glider), #25/6%, #30/4%, #40/4% and #50/4% with reciprocating mode in the root canal (R-Motion, 2019).

Iatrogenic Errors During Root Canal Preparation

In recent years, there has been reported an increase in the complications that occur with the increase in root canal treatment applications (Gorni, et al., 2016). Deviation from the root canal (apical ledge, transport, etc.), fracture of the root canal instrument and canal perforation are among the most common complications in modern dentistry (Borges et al., 2014).

Many studies have suggested that 1-6% and 0.4-5% of endodontic handpieces or rotary instruments break (Parashos, et al., 2006; Spili, et al., 2005; Ungerechts, et al., 2014). It is said that it can prevent the elimination of microorganisms by limiting the entry of the existing broken fragment irrigation solution into the root canal system (Haapasalo, et al., 2003). However, current clinical findings show that the failure rate is not high in the presence of a broken instrument and if root canal treatment is performed by a specialist (Spili, et al., 2005).

Repetitive use of endodontic instruments on root canal walls may cause transport towards the inner radicular wall in the middle of the root, loss of canal curvature and apical transport near the apical foramen. (Oliveira, et al., 2009; Peters, et al., 2015). It has been stated that the lack of sufficient flexibility of a straight metal instrument causes the instrument to be unable to bend so that it remains in the center of a curved canal, thus creating its own path (Honardar, et al., 2014; Özer, 2011).

Such a shift in the canal axis during shaping can lead to loss of excess dentin tissue, resulting in perforation or zip formation in the apical region (Peters, et al., 2015). In cases where the canal transport creates a step, if the instrument used is inclined enough before placing it in the canal, the apical region can be reached by passing the pressing area from the side (Peters, et al., 2015).

Irrigation in the Root Canal System

Disinfection the root canal with irrigation solution is an important step in ensuring optimal bacterial cleaning in the canal system. In areas of the root canal system that cannot be reached mechanically, copious irrigation during cleaning and shaping helps to remove organic debris and tissue debris, to break up microorganisms, and to expose the dentin tubules by removing the smear layer along the canal (Peters, et al., 2015). Due to the anatomical structure of the primary tooth root canals, debridement is performed by chemical rather than mechanical means (Waterhouse & Whitworth, 2016).

The goals of irrigation in endodontics are mechanical, chemical and biological. Mechanical and chemical targets (Basrani & Haapasalo, 2012):

1- Debris removal
2- Lubricating the canal
3- Dissolving organic and inorganic tissues
4- It can be listed as dissolving the smear layer during instrumentation and preventing its recurrence.

The mechanical effectiveness of irrigation will depend on creating optimum flow force within the entire root canal system. Chemical efficacy will vary depending on the concentration of the antimicrobial agent, the area of contact, and the interaction between the irrigation solution and the infected material (Boutsioukis & Kishen, 2012). The final effectiveness of endodontic disinfection will depend on chemical and mechanical activity (Waltimo, et al., 1999).

The biological function of the irrigation solution is related to its antimicrobial effects. Essentially, an irrigation solution should be highly active both in planktonic form and against anaerobic and facultative microorganisms in the biofilm, inactivate endotoxins, be non-toxic in contact with living tissues, and not cause anaphylactic reactions (Basrani & Haapasalo, 2012).

The effectiveness of a canal irrigation in removing debris and eliminating bacteria depends on the depth of penetration of the irrigation needle, the root canal diameter, the inner and outer diameter of the needle, the irrigation pressure, the viscosity of the irrigant, the velocity of the irrigation solution at the tip of the needle, and the type and orientation of the needle bevel. Although there is not an ideal irrigation agent these days, combination of two kinds of irrigation solutions may contribute to successful results of treatment (Peters, et al., 2015).

Features of Ideal Root Canal Irrigants

An ideal irrigation agent:

1) It should be germicide and fungicide.

2) It should not irritate the periapical tissues.

3) It should have prolonged antimicrobial activity.

4) It should be active in the presence of tissue derivatives such as blood, serum and protein.

5) It should have low surface tension.

6) Should not interfere with the repair of periapical tissues.

7) It should not cause a cell-mediated immune response.

8) It should remove the smear layer and disinfect the dentin and tubules underneath.

9) The physical properties of dentin and filling materials should not have adverse effects on their sealing.

10) It should not have negative effects on the physical properties of exposed dentin.

11) It should not cause discoloration of tooth tissues

12) Antigenic, carcinogenic and should not be toxic on dental surrounding tissues.

13) It should be easy to implement and relatively inexpensive (Zehnder, 2006).

Common root canal irrigation solutions. :

- **Sodium hypochlorite (NaOCl)**
- **Chlorhexidine (CHX)**
- **Ethylenediamine tetra-acetic acid (EDTA)**

NaOCl. : Besides its antibacterial capacity, sodium hypochlorite is one of the most commonly used irrigation solutions due to its ability to quickly dissolve necrotic tissues, vital pulp tissues, dentin and organic components of biofilm (Mohammadi, 2008; Senia, et al., 1971).

CHX. : Root canals can be washed with 0.2-2% concentration of chlorhexidine (CHX) or 1-5% concentration of sodium hypochlorite (AAPD, 2016; Ahmed, 2013). Some in vitro studies have shown that NaOCl is more effective at higher concentrations against Enterococcus faecalis and Candida albicans (Gomes, et al., 2001; Radcliffe, et al., 2004). Clinical studies have reported that both low and high concentrations are equally effective in reducing bacteria in the root canal system (Bystrom & Sundqvist, 1985; Cvek, et al., 1976). Higher concentrations of NaOCl have better tissue dissolving effects, however, it should be noted that higher concentrations of NaOCl are more toxic than lower concentrations (Hand, et al., 1978). In the studies, it has been stated that when lower concentrations are used in higher volumes, an equal effect can be obtained with higher concentrations (Moorer & Wesselink, 1982; Siqueira, et al., 2000). Since it is a strong tissue irritant, it should be used carefully in the primary dentition and care should be taken not to overflow from the apex (Goswami, et al., 2014; Klein & Kleier, 2013; Mehdipour, et al., 2007; Zhu, et al., 2013). Canals can be flushed with saline solution before drying with sterile paper points. In many studies, the antibacterial activity of CHX used in infected root canals has been investigated. The antibacterial activity of CHX is concentration dependent. Basrani et al, they showed that 2% CHX had greater antibacterial activity than 0.12% CHX. Ringel et al, they conducted a study comparing the effectiveness of CHX and NaOCl solutions. A study in which infected root canals were irrigated with 2.5% NaOCl and 0.2% CHX for 30 minutes showed that 2.5% NaOCl was significantly more effective (Basrani, et al., 2003; Ringel, et al., 1982).

After canal preparation, a layer containing dentin particles, vital or necrotic pulp residues and bacterial components remains on the root canal walls. This layer is known as the smear layer. Some researchers emphasize that the smear layer should be removed from the root canal in order to increase the penetration of irrigation solutions, medicaments and filling materials into the dentinal tubules (Peters, et al., 2016).

EDTA. : Ethylenediamine tetra-acetic acid (EDTA) alone cannot effectively remove the smear layer. A proteolytic component such as NaOCl should be added to the irrigation procedure to remove the organic components of the smear layer (Goldman, et al., 1976; Siqueira, et al., 1998). EDTA, which is normally used at a concentration of 17%, can remove the smear layer in less than 1 minute when in direct contact with the root canal. The antibacterial activity of EDTA has been shown to be weaker than that of 2.5% NaOCl and 0.2% CHX (Siqueira, et al., 1998).

Imaging Methods Used to Evaluate Root Canal Morphology and Preparation Effects

It has been stated that conventional radiographs can be used in the diagnosis and treatment of pathology and anomalies in the maxillofacial region (Flint, et al., 1998). Conventional clinical radiographs provide 2D projection images (Dowker, et al., 1997). With these data obtained, in the presence of anatomical obstacles such as the canal structure and the presence of thick cortical bone, or in the presence of image disorders such as distortion superimposition, periapical changes may not be revealed accurately (Dogan, et al., 2015; Nair, et al., 2016). These disadvantages of conventional techniques have led to the development of new imaging techniques.

Computed tomography (CT) was first introduced in 1970 by Sir Godfrey Hounsfield. Tomography stands for 'slice imaging', in which thin slices of images obtained from the anatomical region of interest are captured and synthesized. High radiation dose in medical

CT, long scanning time, artifacts caused by metallic restorations, scanning cost and the absence of a dentist-specific software have limited the use of this technology in dentistry until recently (Nair, et al., 2016).

Cone-beam computed tomography (CBCT) imaging is a relatively new diagnostic imaging modality that provides faster, low-dose, relatively high-resolution isotropic images using a more limited field of view, and has recently been used in endodontic imaging. Although the resolution value is not as high as conventional radiographs, CBCT is a preferred imaging method for determining the localization and characterization of root canals, as it provides three-dimensional images and obtains data at a lower dose and higher resolution compared to medical CT (Nair, et al., 2016).

CBCT allows clinicians to examine tooth and pulp structures in thin slices in 3 planes: axial, sagittal and coronal. This feature allows visual monitoring of periapical pathologies and root morphologies that were previously impossible to assess.

While clinical CT devices produce images composed of voxels with a volume of 1mm3, microcomputed tomography is a device that can produce images with a volume of approximately 1,000,000 times smaller than a CT voxel, generated from 5-50 µm voxels, and has better spatial resolution (Swain & Xue, 2009).

A µCT system consists of an X-ray source with a fixed microfocal point, a rotating object, and a high resolution detector (Swain & Xue, 2009). Radiographic projections obtained from different angles by the rotation of the object are used for 3D reconstruction (Sasov & Van, 1998). The data set obtained after the reconstruction can be analyzed in line with the desired parameters. µCT is a non-destructive technique that allows the same sample to be scanned multiple times under different conditions (Swain & Xue, 2009).

In medical CT devices, the rotation of the X-ray source and the detector around the patient causes vibration. However, in the µBT device, the x-ray source and the detector standing still, the rotation of the object around itself reduces the vibration and increases the resolution. However, the X-ray source, which is 1mm in medical CT devices, is 5-10 µm in µBT devices. Smaller X-ray source increases projection sharpness by reducing penumbra (Keles & Alcin, 2015).

Imaging quality in µCT endodontic procedures has been evaluated with different studies (Jung, et al., 2005; Peters, et al., 2001; Peters, et al., 2003). Peters et al. used µCT to evaluate the effect of biomechanical preparation on canal volume and the performance of NiTi instruments on preoperative root canal geometry (Peters, et al., 2001; Peters, et al., 2003). Jung et al. showed in their study that μCT is a very accurate method for the evaluation of filled root canals. However, μCT is currently a research tool and cannot be used on humans (Jung, et al., 2005).

As a result of the current and extensive literature review for the study design; it has been noted that NiTi instruments are generally evaluated in conical shaped canals on factors such as canal transportation, perforation, debris removal, antibacterial activity and working time. Despite these researches, it has been noticed that there is no study yet on the new systems “RaceEvo” and “R-Motion” in the literature. In this study, we aimed to investigate the efficiency of RaceEvo and R-Motion systems for canal transportation and volumetric dentin removal using three-dimensional imaging with CBCT.

CHAPTER III

Methodology

The main focused objectives in the current study titled "Canal Transportation and Volumetric Dentin Removal Abilities of Ni-Ti Rotary File Systems in Curved Primary Root Canals: CBCT Study" are gathered in the following framework:

1) Evaluation of canal transportation efficiency against various accepted endodontic preparation instruments using Race-Evo and R-motion rotary instrument systems, which are newly introduced as rotary instrument systems,

2) Investigation of dentin removal in inclined primary tooth canals by volumetric analysis against various endodontic preparation instruments, by using Race-Evo and R-motion which are newly introduced as rotary instrument systems.

The thesis study named as "Canal Transportation and Volumetric Dentin Removal Abilities of Ni-Ti Rotary File Systems in Curved Primary Root Canals: CBCT Study" was carried out in the clinics of Pediatric and Dental-Maxillofacial Radiology Departments with a bi-disciplinary approach and in vitro procedures. Necessary ethics committee approval before starting the study was retrieved from the "Scientific Research Evaluation Ethics Committee of Near East University" (Ethics Board Approval Certificate, no: 2021/87/1253).

Primarily, our research was evaluated based on the method of measuring dentin removal and canal transportation using CBCT before and after root canal preparation of primary teeth with curved root canal morphology with comparatively Hand-K File, Protaper Gold, RaceEvo and R-Motion systems.

Hypotheses Created to Be Tested Within the Scope of Thesis Study

Considering the canal preparation systems and analysis method used in the research, 6 different hypotheses were determined. These are;

1. "There is a significant difference in the efficiency of volumetric dentin removal between RaceEvo and other root canal preparation systems"
2. "There is a significant difference in the efficiency of volumetric dentin removal between R-Motion and other root canal preparation systems"

3. “There is a significant difference in the efficiency of canal transportation between RaceEvo and other root canal preparation systems”
4. “There is a significant difference in the efficiency of canal transportation between R-Motion and other root canal preparation systems”
5. “There is a significant difference in volumetric dentin removal between RaceEvo and R-Motion systems”
6. “There is a significant difference in canal transportation between RaceEvo and R-Motion systems”

The detailed test steps were planned as follows:

- Selection of samples according to inclusion criteria
- Preparation of samples for models prior to CBCT imaging
- First CBCT imaging phase
- Determination of experimental groups
- Root canal preparation and irrigation of samples
- Second CBCT imaging phase
- Measurement of canal transportation and volumetric dentin removal
- Statistical Analysis

Selection of Samples According to Inclusion Criteria

The teeth that indicated as extraction for various reasons were planned to be used within the scope of current study. Before the extraction of the indicated teeth, the patient who will participate in the study groups were informed about the research and informed consent forms have been signed.

The inclusion citeria of primary molar teeth to be included in the study are set as follows:

✓ Teeth without internal/ external root resorption,
✓ Teeth without root anomaly diagnosis,
✓ Teeth without calcification foci,
✓ Teeth without previous treatment (e.g: root canal treatment),

- ✓ Teeth without cracks or fracture lines,
- ✓ Teeth with two-thirds of the root length remaining.

During the determination of inclusion criteria preoperative images were taken by CBCT to ensure the elimination of either any calcification or internal root resorption for the totally sixty (n=60) primary root canals. The samples were determined based on the Schneider' s technique according to the similarities of their root canal lenghts and curvatures which were approximately 10-20°.

Figure 1

Experimental Samples Including Totally Sixty (n=60) Primary Root Canals

Preparation of Samples for Models Prior to CBCT Imaging

First of all, carious tissue was removed from all selected samples by using a diamond round bur (Meisinger, Germany). Before determining the working length of each root canal, the pulp chambers were irrigated with 1,5% sodium hypochlorite (NaOCl, Cerkamed, Poland) after opening the access cavities. Working lenght was performed by a K-file (#10) (VDW, Munich, Germany) inserted manually into the root canals until the visual apical foramen and evaluated as 1 mm shorter than visual measurement. After the working length was determined, all samples were embedded in waxes up to half of the tooth length.

Figure 2

Figure of a diamond round bur.

Figure 3

Performed working lenght by a K-file (#10).

Figure 4

Wax model design.

First CBCT Imaging Phase

All selected specimens placed in wax models were evaluated by CBCT (Sirona, Bensheim, Germany) with the parameters of 85 kVp, 6 mA, 14.4 s with a 55 mm × 50 mm field of view (FOV) and at a 100 µm isotropic voxel size before the mechanical instrumentation of root canals. The results obtained at the end of the measurements were recorded.

Figure 5

Prepared samples in waxes for CBCT imaging.

Figure 6

Figure of CBCT device used for experiment.

Determination of Experimental Groups

Within the scope of the study, the experimental groups were randomly divided into 4 groups (n=15/each) according to the root canal shaping system.

Group I: Manual nickel-titanium (Ni-Ti) K-files (VDW, Munich, Germany)

Group II: Protaper Gold Rotary System (Maillefer, Dentsply, Switzerland)

Group III: RaceEvo Rotary System (FKG, Switzerland)

Group IV: R-Motion Rotary System (FKG, Switzerland)

Figure 7

Experimental groups arranged in the study.

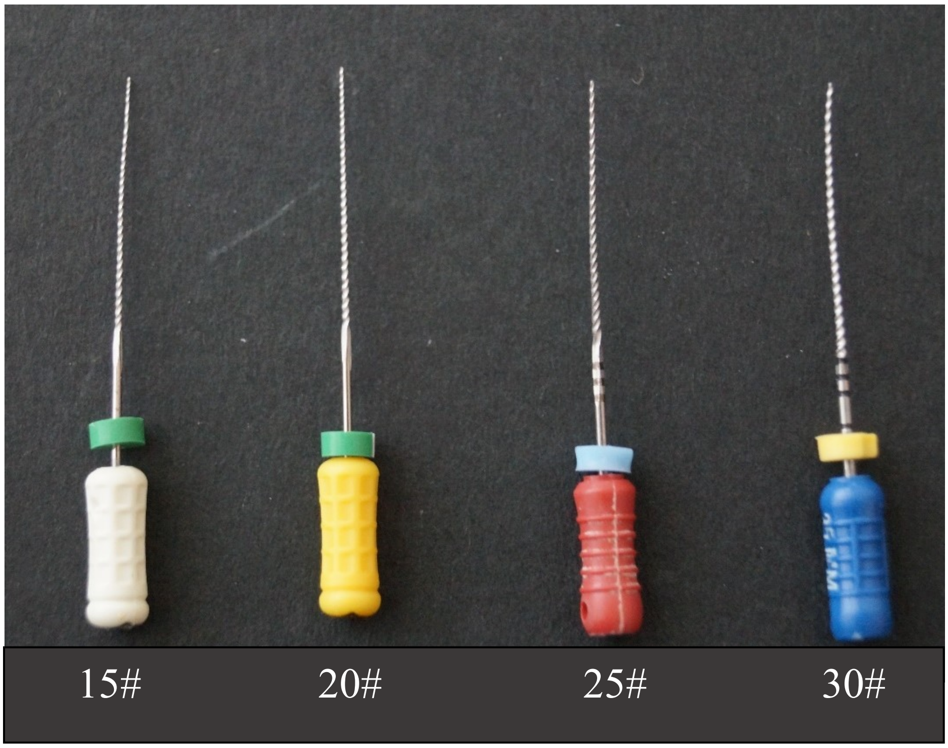
RaceEvo	**R-Motion**	**Protaper Gold**	**Manual**

Root Canal Preparation and Irrigation of Samples

The samples belonging to **Group I** (n=15) were manually instrumented with a Ni-Ti K-file by using the step back technique. For the mechanical preparation of the teeth in this group, files up to #30 were applied respectively within the limitation of working lenght. Finally #30 size file was conducted in order to inhibit ledge formation.

Figure 8

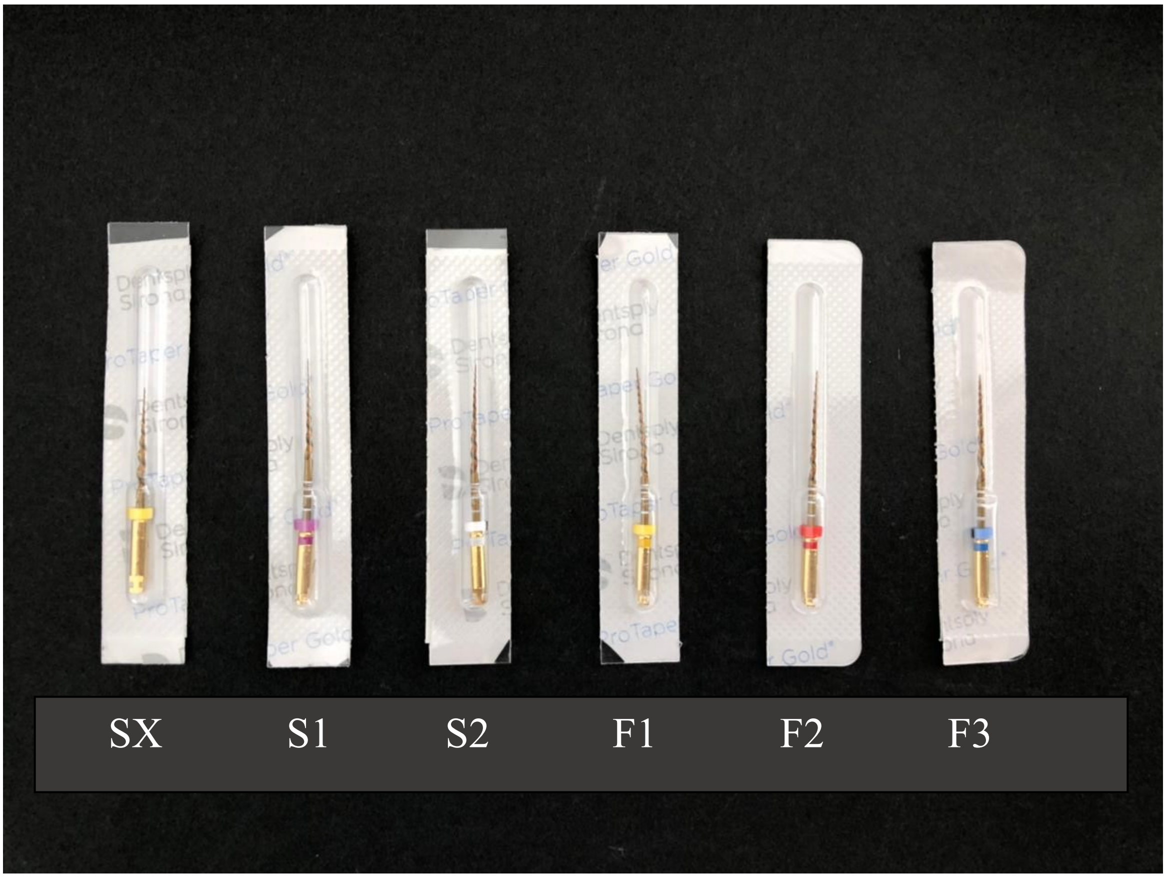
Manual Ni-Ti K-files.



In **Group II**; totally the number of fifteen canals (n=15) were instrumented by the Protaper Gold Rotary System upto F3 size. The files were operated using a motor named X-smart Plus (Maillefer, Dentsply, Switzerland) with 300 rpm and 5 Ncm torque parameters. The file order used in this system was as follows: Sx, S1, S2, F1, F2, and F3. Sx, S1 and S2 were used in the brushing action mode, while others (F1, F2, F3) were with non-brushing action. Sx was used until the file was over against with resistance; S1 was used until 1 mm shorter than the working lenght in order to ascertain the radicular access; and S2 was used until the working lenght. F1, F2 and F3 files were used for the finishing preparation of root canals until the working lenght which each insertion was deeper than the previous one.

Figure 9

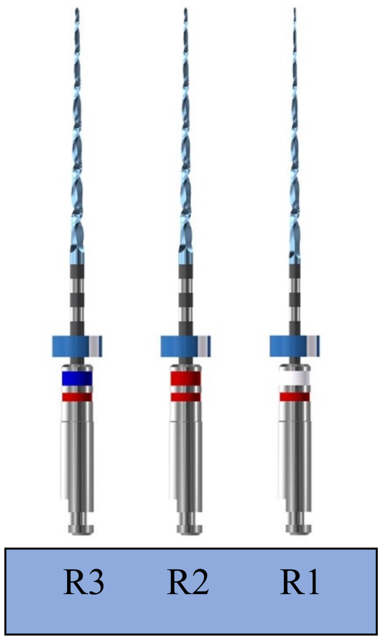
Protaper Gold rotary files.



In the RaceEvo Rotary System (FKG, Switzerland) group, also called **Group III**, fifteen root canals (n=15) were prepared with R1, R2 and R3 rotary files (size of 15,25,30, respectively) with 4% tapers. 800 rpm of speed range with continuous rotation and 1.5 Ncm of torque parameters were adjusted for X-smart Plus motor. The order of files used for shaping were as R1, R2 and R3 respectively. Immediately removal of each file that reached the working lenght was recommended to prevent the over enlargement of apical foramen.

Figure 10

RaceEvo rotary files.



Finally in **Group IV**; a total of fifteen (n=15) curved primary root canals were prepared by using a size of 15/R-Motion Glidder, 25/R-Motion 25 and 30/R-Motion 30 files with the tapers of 0.03, 0.06 and 0.04, respectively. In this R-Motion Rotary System (FKG, Switzerland); only the standard reciprocating mode was used as 170° counterclockwise and 50° clockwise rotations. The first instrument, R-Motion Glidder; was used to form a glide path until the working lenght and this procedure was continued with files R-Motion 25 and R-Motion 30. Each file was quickly withdrawn as soon as it reached working length to prevent the enlargement of apical foramen.

Figure 11

R-Motion rotary files.

Another important issue applied in the study was irrigation of root canals during preparation. After each file use in all groups, the canals were abundantly irrigated with 1.5% sodium hypochlorite (NaOCl) and saline solution.

Second CBCT Imaging Phase

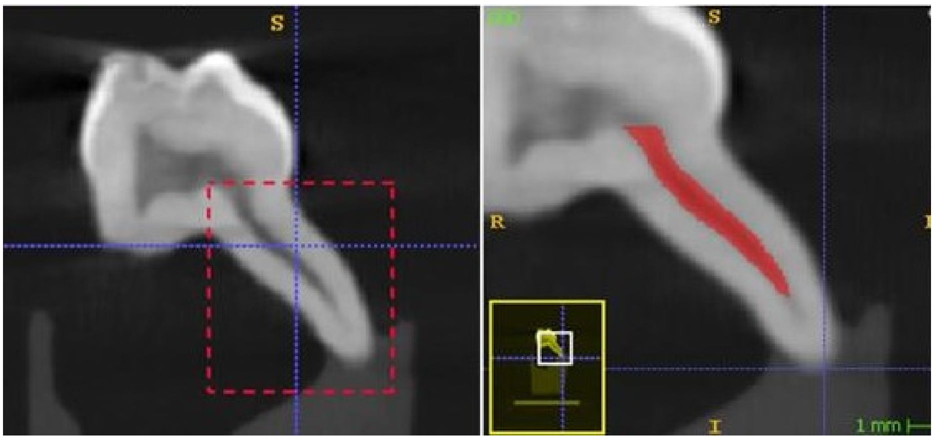
After completion of all preparation and irrigation procedures according to the experimental groups, CBCT images were obtained again from all samples. The parameters belonging to CBCT were as follows: 85 kVp, 6 mA, and 14.4 s with a 55 mm × 50 mm FOV. Again all measurements were recorded.

Measurement of Canal Transportation and Volumetric Dentin Removal

While CBCT images were taken for each root canal in the canal transport measurement, an illusory line passing over the furcation region was designed in three-dimensional environment and the measurements were carried out. Due to the different working lengths of the root canals; root lengths were divided into 3 parts (superior 1/3, middle 1/3 and apical 1/3) and evaluated individually. In order to prevent measurement errors caused by minor angulation differences, pre- and post-operative axial slices of each root were superimposed by using On Demand 3Ds, On Demand3D Fusion (Cybermed Inc., Seoul, Korea) software. Measurements for canal transportation were evaluated using images from the first and second CBCT imaging phases and the overall canal transportation values were determined by the differences between pre- and post-operative calculations following the implementation of both designs.

Figure 12

Illusory line passing over the furcation region.



The volumetric determination of dentin removal was carried out using Orthophos SL 3D CBCT Unit (Dentsply Sirona, Erlangen, Germany) and the pre-operative (T1) and post-operative images (T2) were kept as DICOM files. All the images were analysed the ITK-SNAP version 3.6.0 (www.itksnap.org), an open-access image analysis software which was used for volumetric analysis on the 3D images. The Active Contour (Snake) Segmentation Mode had been applied to dispose of crown, air and other roots outside the region of interest

(ROI) and achieve faster segmentation. Pre-segmentation mode for root canals was based on "thresholding" which was set between -1024 and 1200 GV. After the segmentation procedure; bubbles with a radius of 0.4 mm were inserted in the "white" region which exemplifies the multiple root canal spots and contour evolution was revealed. The volumes and statistics option was chosen from the segmentation toolbox prior to the voxel count, volume in mm3 and intensity mean with standard deviation recording. Volumetric datas for each single root canal were recorded for both phases as VT1; for pre-operative and VT2; for post-operative volumetric CBCT images and volumetric dentin removal calculations were set as follows: [VT1 – VT2].

Figure 13

Thresholding for segmentation of the primary root canal to determine volumetric dentin removal

*(**A**) Active contour "Snake" segmentation window; (**B**) Pre-segmentation speed image of a single primary root canal with threshold between -1024 and 1200 GV; (**C**) Bubble placement to initialize the contour with 1.20 mm radius red bubbles; (**D**) Post-execution speed image of the root canal (red areas); (**E**) Final image of the primary root canal*

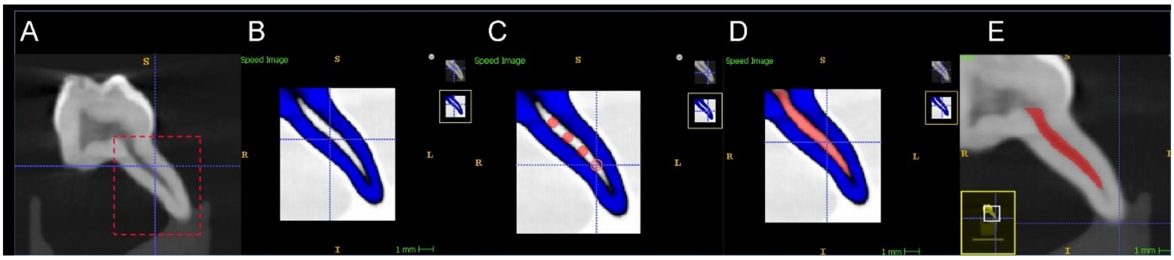
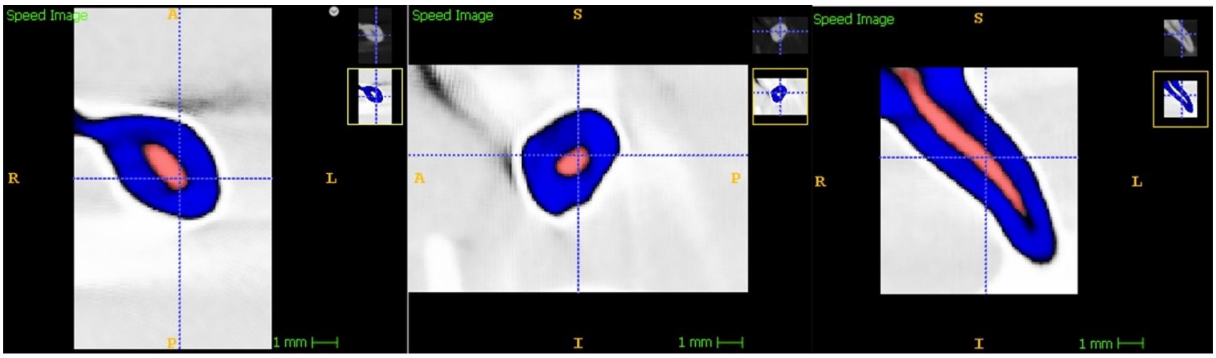


Figure 14

Multiplanar images of a single primary root canal.



Statistical Analysis

All the datas for each analysis were initially checked for normality. As all the datas were not distributed normally; different analitic tests were used for the differences between comparable groups as; non-parametric Kruskal–Wallis and Dunn's post hoc tests. The significance value was accepted as 0.05 and the software utilized for all analyses was GraphPad Prism software (version 8.1.1, San Diego, CA, USA) and SPSS (version 20.0, Chicago, IL, USA).

CHAPTER IV

Findings and Discussion

The measurements of images collected from the first and second CBCT phase in the present study were compared according to two determinations:

1) Canal transportation

2) Volumetric dentin removal.

Evaluation of Canal Transportation

The mean values of each group were calculated separately. As a result; significant differences between experimental groups were obtained in multiple comparisons of the canal transportation values. Canal transportation was significantly achieved as the highest degree in the ProTaper Gold rotary system (0.2255 ± 0.015) when compared to with RaceEvo and R-Motion rotary systems (0.1329 ± 0.013/p = 0.0002; 0.1386 ± 0.014/p = 0.0006, respectively). No statistical significance was found in any other data comparing canal transportation. Multiple comparisons of canal transportation within study groups are presented in Table 1 and additionally mean values and comparative measurements (first and second CBCT imaging phases) of canal transportation in groups are represented as Figure 15 and 16, respectively.

Table 1.

*Multiple Comparisons of Canal Transportation Across Experimental Groups (Results are expressed as mean values ± SEM). (*** p < 0.001)*

Multiple Comparisons of Canal Transportation Across Experimental Groups			*P* value
Race Evo vs R-Motion	0,1329±0,013	0,1386±0.014	> 0,9999
Race Evo vs ProTaper Gold	0,1329±0,013	0.2255±0.015	**0,0002*****
Race Evo vs Manual	0,1329±0,013	0.1781±0.016	0,2086
R-Motion vs ProTaper Gold	0,1386±0.014	0.2255±0.015	**0,0006*****
R-Motion vs Manual	0,1386±0.014	0.1781±0.016	0,4603
ProTaper Gold vs Manual	0.2255±0.015	0.1781±0.016	0,2126

Figure 15

*Canal transportation across experimental groups. Results are expressed as mean values ± SEM. (*** p < 0.001)*

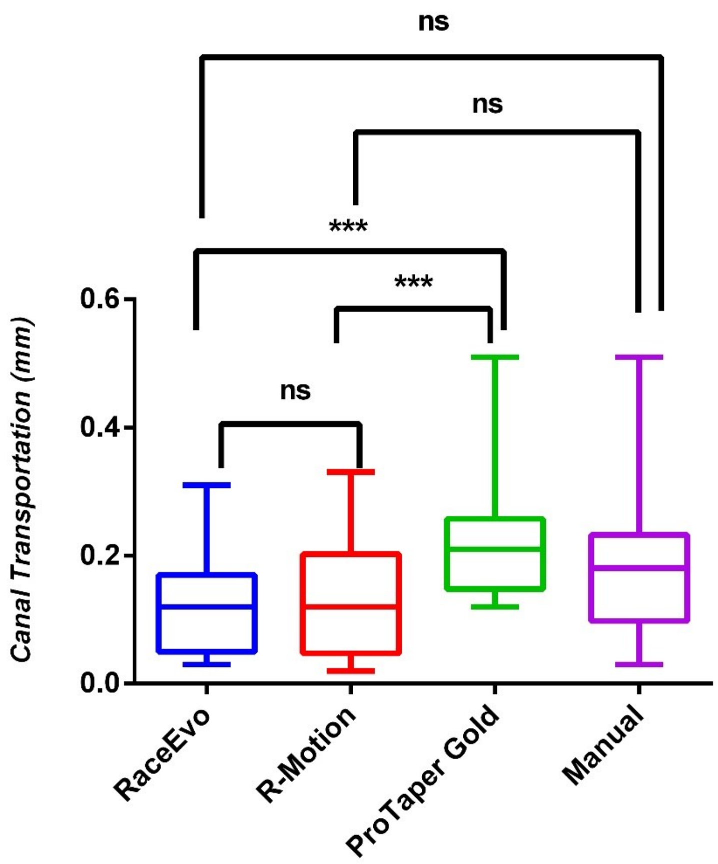
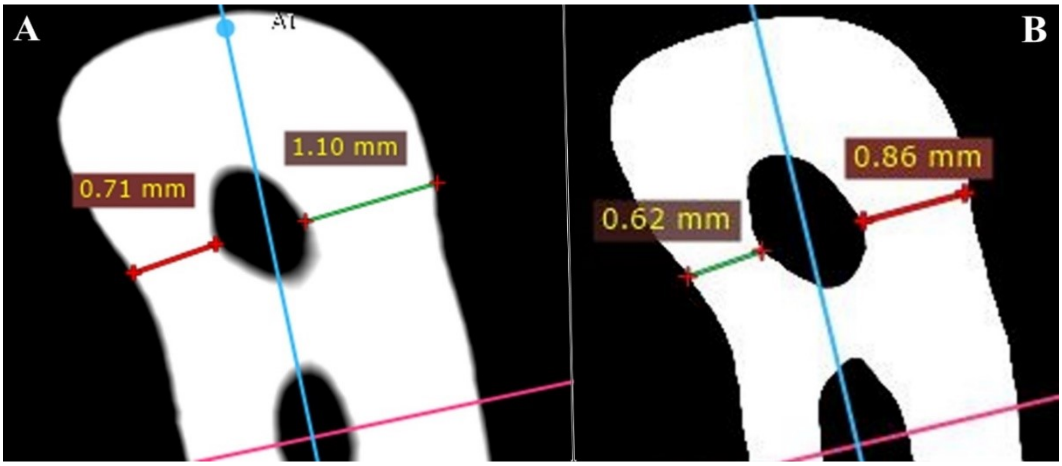


Figure 16

Measurements of root canal transportation.

*(**A**) Before instrumentation (**B**) After instrumentation.*



Evaluation of Volumetric Dentin Removal

In the intergroup volumetric dental removal analysis, Protaper Gold system showed the highest significant value again, when compared to the RaceEvo, R-Motion and Manual instrumentation groups (0.4629 ± 0.018; 0.4957 ± 0.018; 0.8427 ± 0.12, respectively / $p = 0.000$ for all comparisons). However; there was no significant difference between RaceEvo and R-Motion rotary systems ($p > 0.05$) in terms of volumetric dentin removal. Over and above; manual instrumentation group exhibited higher value of volumetric dentin removal in comparison with RaceEvo and R-Motion rotary systems ($p = 0.014$; $p = 0.027$, respectively). The mean values of volumetric dentin removal in all study groups are presented in Table 2 and Figure 17. Moreover; three-dimensional image reconstructions belong to first and second CBCT imaging phases are given in Figure 18.

Table 2

*Multiple comparisons of volumetric dentin removal across experimental groups. (Results are given as mean values ± SEM). (*** p < 0.001, * p < 0.1)*

Multiple Comparisons of Groups			***P value***
Race Evo vs R-Motion	0,4629±0,018	0,4957±0,017	*0.679*
Race Evo vs ProTaper Gold	0,4629±0,019	2,015±0,074	***0,000****
Race Evo vs Manual	0,4629±0,020	0,8427±0,11	***0,014****
R-Motion vs ProTaper Gold	0,4957±0,017	2,015±0,074	***0,000****
R-Motion vs Manual	0,4957±0,018	0,8427±0,11	***0,027****
ProTaper Gold vs Manual	2,015±0,074	0,8427±0,12	***0,000****

Figure 17

*Volumetric dentin removal across experimental groups. Results are given as mean values ± SEM. (*** p < 0.001)*

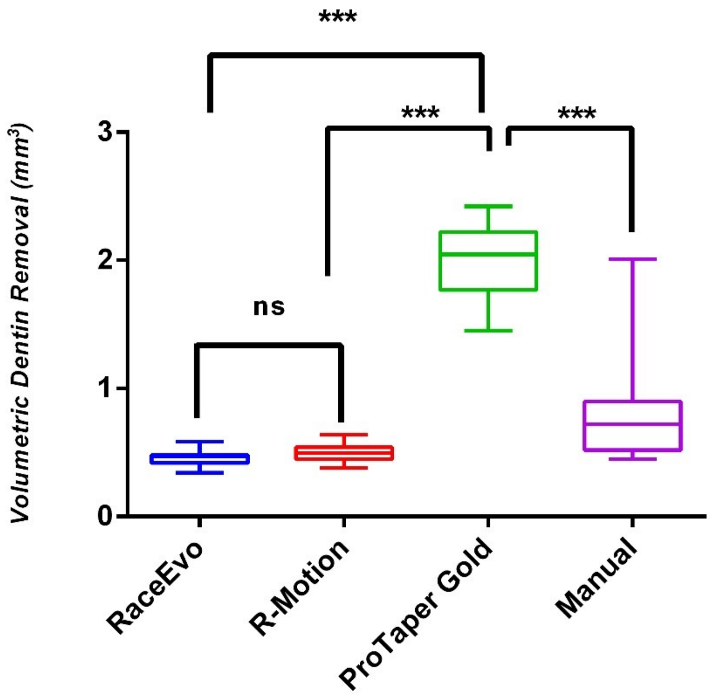


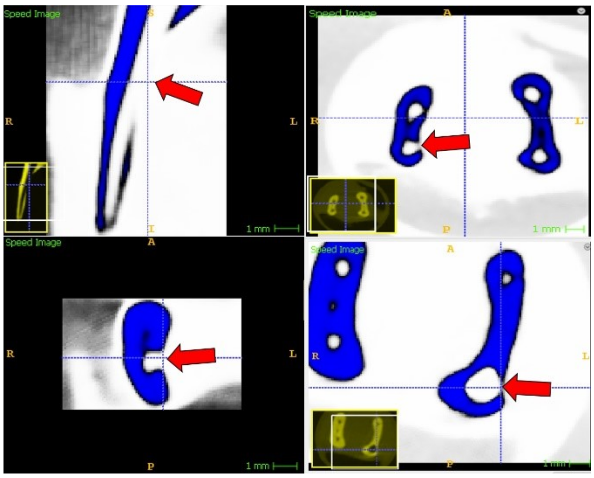
Figure 18

*Buccolingual views of preoperative (red) and postoperative (yellow) root canal threedimensional (3D) reconstruction images of a primary mandibular molar tooth (reconstructed from an exported surface mesh STL data). (**A**) Preoperative-3D buccolingual view of a root canal; (**B**) Postoperative-3D buccolingual view of a root canal.*

In the current study, radiographic achievement of all groups were evaluated as well. As a result of this evaluation; ProTaper Gold rotary system caused perforations of four decidious root canals and one root canal was detected with perforation in the manual group; whereas no perforation was found in both R-Motion and RaceEvo groups. All of the root canals with perforation were renewed with the news and all procedures came round.

Figure 19

Speed images of perforated root canals that were excluded from the study.



CHAPTER V

Discussion

Although there are opinions that rotary endodontic instruments, which have many importance in the past ten years, can cause significant differences in root canal treatments of primary teeth; no exact and optimal endodontic instrument has been developed specifically for primary teeth. For this purpose, different root canal preparation methods and/or instruments used for permanent teeth, are also under review for the primary teeth (Ahmed, 2013). There are studies evaluating the effectiveness of different root canal preparations in root canal treatment of primary teeth which have been reported in the literature (Crespo, et al., 2018; Kummer, et al., 2008; Musale & Mujawar, 2014). In the current study, various endodontic rotary systems (Protaper Gold, RaceEvo, R-Motion) were preferred to determine and comparatively investigate the canal transportation and volumetric dentin removal on curved roots of primary teeth, by the traditionally usage of hand files as the control group in which there is no previous study related with RaceEvo and R-Motion rotary systems.

In order to help the removal of organic and inorganic residues, besides shaping the root canals, an instrumentation that maintains the structure of the tortuous root canal anatomy of primary molars from apical to coronal with sufficient dentin thickness is also noteworthy (Grande et al, 2008). However, a variety of procedural errors, including as canal transportation and dentin removal difficulties, can result in decreased fracture resistance, jeopardizing the original canal curvature, increasing the chance of debris ejection, and causing postoperative pain (Lopez, et al., 2008; Shahriari, et al., 2009).

When the literature is reviewed, current advancements in rotary Ni-Ti file systems have resulted in a paradigm change in primary tooth root canal therapy. Hence, a detailed evaluation of the efficiency of newly developed root canal shaping equipment in terms of many characteristics is required. From this necessity, the performance of the relatively new RaceEvo, R-Motion, and ProTaper Gold systems in curved primary root canals in terms of canal transportation patterns and volumetric dentin removal was compared and evaluated by using CBCT.

In the present study, the included samples were chosen very carefully and each step was attentively controlled. Also, the clinical conditions were simulated as much as possible by using extracted primary human teeth. The absence of root fracture/crack and any rot on the root were taken into selection with the closed apices. Although in many studies evaluating the efficacy of root canal preparation in primary teeth; the condition that there is limited resorption or that the root length is at least 8 mm, in the inclusion criteria; the current study two-thirds of the root length remaining was determined (Crespo, et al., 2018; Kummer, et al., 2008; Musale & Mujawar, 2014).

A detailed understanding of the complex root canal system is important for root canal treatment. In studies examining the effect of the preparation on canal anatomy in extracted human teeth, different evaluation methods were used. Paque et al., in order to make a comfortable preparation and for easy access to root canals, the teeth were held in the hand throughout the procedure (Paque, et al., 2005). In our study, in line with this view, the teeth were held by hand during the preparation phase.

In order to analyze different instrumentation parameters, various approaches involving serial sectioning, microscopic investigations, muffle systems, radiography, silicone impressions, endodontic tubes, multislice computed tomography, CBCT, and others were discussed (Musale, et al., 2019). The fact that information obtained from periapical radiographs is limited to two dimensions; advance technologies brought to the fore three-dimensional images (Canoglu, et al., 2006). In the modern endodontic field, CBCT has grown in popularity and is a preferred alternative tool for evaluating three-dimensional (3D) root canal anatomy, determining the amount of dentin to be removed, measuring canal transportation, centering ability, and conducting comparisons between before and after root canal instrumentation. The volumetric units of enamel, dentin, and pulp tissues can also be measured and calculated using CBCT (Adisen, et al., 2015; Musale, et al., 2019). Due to these advantages, CBCT was used in this study to identify the included criteria and evaluate the characteristics of overall canal transportation and volumetric dentin removal patterns in curved primary root canals prepared with manual and various rotary instruments techniques.

The key measure used to evaluate the shaping efficacy of the tested instruments in each experimental group was the determination of canal transportation patterns. The overall canal transportation for each prepared root canal length was assessed. When comparing the newly developed RaceEvo and R-motion rotary systems to the ProTaper Gold (PTG) rotary system for overall canal transportation analysis, the results showed that the newly developed RaceEvo and R-motion rotary systems clearly exhibited fewer canal transportation complications, while preserving the original curved root canal shapes following instrumentation. Conversely, the PTG group has the highest average transportation values.

These significant disparities could be related to the examined instruments' manufacturing procedures and characterizations. Thinner core diameters, improved flexibility, rounded triangular cross-sections with sharp cutting edges, and new optimized file tips were all designed into R-Motion rotary system instruments (FKG R-Motion, 2021). In light of this, the R-Motion rotational systems, when compared to PTG systems, give superior respect for the curved primary root canal anatomy without producing substantial canal transportation difficulties while preserving and lowering dentinal tissue stress. Furthermore, the difference in mean transportation levels between R-Motion and PTG rotary systems could be explained by the R-Motion rotary systems' reduced screwing effect design, which allows the clinician to provide a higher level of control efficiency during root canal development (FKG R-Motion, 2021). In comparison to PTG and manual instrumentation, the RaceEvo rotary system had a similar efficiency in canal transportation with R-Motion. RaceEvo rotary systems are made with a heat-treated procedure and a greater rotation speed performance design. RaceEvo's sharp-edged, triangular design, combined with high-speed performance and a heat treatment technique, provides various benefits, including increased flexibility, cyclic fatigue resistance, and cutting efficiency (FKG RaceEvo, 2021). According to the current findings of the present study, RaceEvo's remarkable performance in keeping the original root canal geometry without causing detrimental canal transportation impacts can be explained. Although the results of this study could not be directly compared to those of Hashem et al and Agarwal et al due to the use of different systems and methodology, their major findings about PTG systems were compatible with the findings of this study (Agarwal, et al., 2015; Hashem, et al., 2012). PTG systems were shown to have the highest number of canal transportation rates in each of these investigations. Another factor that has an inverse effect on canal shipping patterns is instrument tapering. Because of their apical enlargement and increased canal transportation ratios in curved root canals, Ni-Ti files with taper sizes greater than 0.04 (4%) are not advised, according to studies on instrument tapering and canal transportation interactions (Boscornea-Puşcu, et al., 2021; Reham, et al., 2018). Both the RaceEvo and R-Motion systems were employed with 4% tapers in this study, whereas the PTG system was used until it reached F3 (0.09/9% taper) size to ensure consistency. As a result, the discovery of a higher canal transportation rate in the PTG system compared to RaceEvo and R-Motion systems may be better explained and is consistent with earlier researches (Hashem, et al., 2012; Reham, et al., 2018; Singh, et al., 2019).

There have been a few studies on the effectiveness of these newly developed R-Motion and RaceEvo rotary systems on primary curved root canals (Al Omari, et al., 2021; De Deus, et al., 2021). The ability to compare the tested newly built systems to prior research in terms of canal transportation and volumetric dentin removal is extremely limited.

Importantly, the current study compared the quantitative volumetric dentin removal patterns of employed instruments in curved primary root canals to better understand the utility of these new rotary devices in the primary dentition. The volumetric dentin removal findings revealed substantial variations between the groups. The PTG rotary group had the greatest mean value of volumetric dentin removal in the current investigation. When compared to RaceEvo and R-Motion rotary groups, the PTG rotary and manual instrumentation groups exhibited higher mean values of volumetric dentin removal. The convex triangular cross-section and progressive taper design, which intensify the cutting action and result in aggressive cutting side effects on the dentin surface, may explain the PTG rotary group's aggressive attitude in curved primary root canals (Dentsply Protaper Gold, 2021). Although there was little variation in the pattern of volumetric dentin removal between the manual instrumentation group and the RaceEvo and R-Motion rotary groups, the RaceEvo and R-Motion rotary groups generated superior results. This could be attributable to the operator's high level of performance during instrumentation. Eventhough there was no quantitative volumetric analysis performed, the findings of Kummer et al. and Musale et al. are partially consistent with the findings of the current study, in that the amount of volumetric dentin removal with the manual instrumentation technique was significantly higher than the rotary groups, with the exception of the PTG group (Kummer, et al., 2008; Musale, et al., 2019).

Ni-Ti wires have gained favor in dentistry in recent years due to their form memory and extraordinary flexibility. The alloys gain these qualities as a result of a specific phase shift that occurs during the transition from austenite to martensite forms (Tabassum, et al., 2019). Medical-grade Ni-Ti alloy with a triangular symmetrical cross-section with sharp edges was used in the current study for the RaceEvo and R-Motion rotary groups. Both rotary groups' active portions were subjected to a patented heat treatment that produced the above-mentioned phase transition (between martensite and austenite) just below body temperature, i.e. between 32 °C and 35 °C (FKG RaceEvo, 2021; FKG R-Motion, 2021). Furthermore, thermomechanical treatment of Ni-Ti alloy instruments prevents straightening of instruments in curved root canals during preparation and results in less root canal transportation with adequate shaping abilities (Silva, et al., 2020). In contrast to all other examined rotary and hand instruments in the study, PTG rotary devices frequently use a patented heat-treatment mechanism termed controlled memory wire (CM wire) instead of heat-treated Ni-Ti wire. Instruments made with CM wire have been shown to have superior flexibility and resistance during root canal preparation, minimizing the risk of problems such deviation, instrument fracture, and perforation (Duque, et al., 2017; Pereira, et al., 2018). When interpreting the tested instruments from the standpoint of influence of shape and alloy features on canal transportation and volumetric dentin removal parameters, RaceEvo and R-Motion rotary groups exhibited superior abilities in terms of canal transportation and volumetric dentin removal parameters than the PTG group and manual instrumentation, despite these improved physical characteristics of PTG rotary systems with CM wire manufacturing. The progressive taper (9% taper size—F3) and increased cutting efficiency with a convex triangular cross-sectional shape could explain these unanticipated discrepancies (Dentsply Protaper Gold, 2021).

"The importance and effect of reciprocating motion" is another essential topic that should be studied and compared. Roane et al. were the first to present the reciprocating motion, which they reasoned as a balanced force during instrumentation based on rules of action and reaction (Roane, et al., 1985). Reciprocal motion reduces the taper lock effect of the instrument during canal preparation, which reduces flexural strains and allows for increased canal centering ability. From the perspective of pediatric endodontics, the use of reciprocating motion rather than continuous rotation in curved root canal preparation could minimize stress and time (Nishijo, et al., 2018). With these considerations in mind, R-Motion's superior outcomes in terms of canal transportation and volumetric dentin removal when compared to the PTG and manual instrumentation groups may be supported and understood from a differential standpoint. Furthermore, the superiority of reciprocating motion in this investigation was partially consistent with Prabhakar et al' s findings (Prabhakar, et al., 2016).

The Hounsfield units (HUs), which were employed for thresholding and are not as trustworthy as CT units, were a key limitation of the current investigation. The use of HUs in CBCT raises a number of challenges, including limited-field CBCT geometry, basic principles of radiation physics, and the limitations of commonly utilized reconstructive techniques. On the other hand, CT units do not contain isotropic voxels or thin slice thicknesses like CBCT units (less than 1 mm), which are important for studying small, narrow anatomical structures like root canals. At these scales, HUs are deemed dependable. Grayscale values (GVs) are sometimes employed instead of HUs in CBCT, resulting in several inaccuracies, such as:

- the existence of beam hardening, cupping, and doming artifacts;
- the X-ray beam's divergence;
- variability in axial slices due to varying mass of each slice;
- high image noise (which has a limited impact on small-region tests like the ones used in this study);
- some manufacturers do not include GV calibrations in their CBCT systems;
- various CBCT models have different GVs for the same matter (Molteni, et al., 2013; Pauwels, et al., 2014; Pauwels, et al., 2015; Schulze, et al., 2011).

As an important point, Pauwels et al. showed that GVs can vary depending on the CBCT device, the quantity of mass inside and beyond the field of view, the matter's central/peripheral placement, and exposure parameters (Pauwels et al, 2014; Pauwels et al, 2015). The main goal of this study was to compare different root canal instrumentation systems. Hence, all of the images were taken using the same CBCT unit, thresholding, imaging parameters, and location to minimize the consequences of this constraint.

CHAPTER VI

Conclusion and Recommendations

Within the confines of the aforementioned constraints and the current study's tested parameters, the following findings can be drawn:

- In comparison to ProTaper Gold and manual instrumentation approaches, the newly developed R-Motion and RaceEvo rotary devices produced greater preparative results by causing less overall canal transportation and volumetric dentin removal;
- When compared to ProTaper Gold rotary systems with manual instrumentation, R-Motion and RaceEvo rotary systems could be a trustworthy option without generating negative mechanical effects and keeping original root canal morphology of curved primary root canal systems;
- The first hypothesis which “There is a significant difference in the efficiency of volumetric dentin removal between RaceEvo and other root canal preparation systems” was partially accepted.
- The second hypothesis which “There is a significant difference in the efficiency of volumetric dentin removal between R-Motion and other root canal preparation systems” was partially accepted.
- The third hypothesis which “There is a significant difference in the efficiency of canal transportation between RaceEvo and other root canal preparation systems” was partially accepted.
- The fourth hypothesis which “There is a significant difference in the efficiency of canal transportation between R-Motion and other root canal preparation systems” was partially accepted.
- The fifth hypothesis which “There is a significant difference in volumetric dentin removal between RaceEvo and R-Motion systems” was rejected.
- The last hypothesis which “There is a significant difference in canal transportation between RaceEvo and R-Motion systems” was also rejected.

More evidence-based research using extensive CBCT analyses to assess the capacities of newly developed rotary devices on curved main root canals are needed.

Furthermore, more in vivo studies are required and strongly advised to determine the impact of more severe and complex primary root canal curvatures, various demanding environmental conditions, or different surface treatment processes on newly manufactured instruments.

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APPENDICES

Appendix 1

YAKIN DOĞU ÜNİVERSİTESİ
BİLİMSEL ARAŞTIRMALAR ETİK KURULU

ARAŞTIRMA PROJESİ DEĞERLENDİRME RAPORU

Toplantı Tarihi : 28.01.2021

Toplantı No **:** 2021/87

Proje No **:**1253

Yakın Doğu Üniversitesi Diş Hekimliği Fakültesi öğretim üyelerinden Yrd. Doç. Dr. Aylin İslam'ın sorumlu araştırmacısı olduğu, YDU/2021/87-1253 proje numaralı ve **"Süt Dişi Kök Kanal Preparasyonlarında Kullanılan Farklı Döner Alet Sistemlerinin Oluşturduğu Kanal Transportasyonları ve Uzaklaştırılan Dentin Kalınlıklarının Konik Işınlı Bilgisayarlı Tomografi ile Değerlendirilmesi"** başlıklı proje önerisi kurulumuzca online toplantıda değerlendirilmiş olup, etik olarak uygun bulunmuştur.

Prof. Dr. Rüştü Onur

Yakın Doğu Üniversitesi

Bilimsel Araştırmalar Etik Kurulu Başkanı

Appendix 2

Ala Tez 27.12.2021

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6. Publication : İslam, A., Ünsal, G., & Almashharawi, A. (2021). Canal Transportation and Volumetric Dentin Removal Abilities of Ni-Ti Rotary File Systems in Curved Primary Root Canals: CBCT Study. *Applied Sciences*, *11*(19), 9053.