

Root Canal Preparation with Two Different Rotary Systems: Comparative Study Assessed By Micro-computed Tomography

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ABSTRACT

Title Root canal preparation with two different rotary systems: comparative study assessed by micro-computed tomography.

Aim To evaluate, using micro-computed tomography, the root canal transportation and centering ability of BioRaCe and AlphaKite rotary instruments, and their ability to eradicate canal variations after preparation of the mesiobuccal root of the first maxillary molar tooth.

Methodology Mesiobuccal roots of 20 maxillary first molars with similar angles of curvature were divided randomly into two groups and scanned using a SkyScan 1172 micro-CT scanner (SkyScan N.V., Aartselaar, Belgium). Root canals were then prepared with BioRaCe (FKG Dentaire, La Chaux-de-Fonds, Switzerland) or AlphaKite (Komet, Lemgo, Germany) instruments. The prepared roots were re-scanned and cross-sectional images of the pre- and post-instrumentation scans were reconstructed using the SkyScan reconstruction software. The amount of transportation was assessed quantitatively using the cross-sectional images by measuring the shortest distance from the edge of the uninstrumented canal to the periphery of the root (mesial and distal) and then comparing this with the same measurements obtained from the instrumented images. A negative result indicates transportation toward the distal surface of the root (inner curvature), a positive result toward the mesial surface (outer curvature), and nil, the absence of transportation. The centering ratio was calculated by using a formula in which a result of '1' indicates perfect centering. Student *t*-tests and ANOVA tests were used for statistical analysis. Three- dimensional images of the root canals were then reconstructed using the appropriate software (Amira 4.1; Visage Imaging Inc., USA), to evaluate eradication of canal variations by the two instruments.

Results The average canal transportation with BioRaCe instruments at the coronal, middle and apical thirds were, -0.12 ± 0.19, -0.01 ± 0.09 and +0.06 ± 0.05 mm, respectively, with a significant difference ($P < 0.05$) in the amount of transportation between the coronal and apical levels. The average canal transportation with AlphaKite instruments in the coronal, middle and apical thirds were -0.05 ± 0.22, -0.04 ± 0.10 and +0.03 ± 0.03 mm, respectively, with no significant difference between the levels ($P > 0.05$). Centering ratio using BioRaCe at the coronal (0.32 ± 0.25), middle (0.53 ± 0.23), and apical (0.57 ± 0.27) thirds showed no significant difference between the levels ($P > 0.05$). For the AlphaKite system, the centering ratio results were (0.46 ± 0.31) for the coronal, (0.56 ± 0.29) for the middle and (0.66 ± 0.24) for the apical thirds. No significant difference was found between the levels ($P > 0.05$). There was no statistically significant difference between the systems in regard to canal transportation and their centering ability across all levels ($P > 0.05$). Neither was able

to completely eradicate canal variations of the mesiobuccal root of maxillary first molars.

Conclusions Within the limitations of this *ex vivo* study, the two new nickel-titanium instruments produced moderately well centered canals with minimal canal transportation. The complex anatomy of the mesiobuccal root of maxillary first molars was confirmed.

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CHAPTER 1: INTRODUCTION

The key factor in the development of pulpal inflammation and apical periodontitis is bacteria. It has been widely accepted that bacteria and their by products are the main aetiological factors in the initiation and progression of these diseases (Bergenholtz 1990). As a result, the central focus of root canal treatment has been directed towards the elimination of bacteria and their substrates from the root canal system. Knowledge of canal anatomy is therefore important for successful root canal treatment outcomes.

Mechanical preparation of the root canal system is recognized as being one of the most important stages in root canal therapy. Problems with breakage and the inflexibility of stainless steel hand instruments have led to the search for new materials from which to fabricate endodontic instruments. Following the introduction of nickel-titanium (NiTi) rotary instruments, instrumentation of the root canal system became easier and faster, the shaping outcome became more consistent and predictable, with considerably less iatrogenic damage (Hülsmann *et al.* 2005).

Over the years, new NiTi instruments with different tapers and designs have been introduced to the market. The endodontic literature is replete with studies on the various aspects of NiTi instruments' performance in canal preparation such as the cleanliness of the canals after preparation, the shaping ability of the instruments and their fracture properties. Several methodologies have been described to evaluate these instrumentation parameters, including serial sectioning and radiographs. Micro-computed tomography has been advocated as a noninvasive experimental method for the comparison of pre- and post-instrumentation images of root canals. With this technique, it is possible to evaluate root canals three-dimensionally.

More and more studies on new NiTi instruments are required to understand how new design features may affect their performance. Consequently, the aim of the

present study was to investigate the shaping properties of two new NiTi systems: BioRaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) and AlphaKite (Komet, Lemgo, Germany). Two parameters were evaluated: canal transportation and the centering ability of the two new systems. Micro-computed tomography was used as the main experimental tool. In addition, the two systems were evaluated on their ability to eradicate canal variations of the mesiobuccal root of maxillary first molars. The mesiobuccal root was chosen for this study because of its complex root canal anatomy (Cleghorn *et al.* 2006).

The next chapter of this thesis includes a review of the literature on the mesiobuccal root of the maxillary first molar, mechanical root canal preparation and micro-computed tomography. Materials and methods used in this study are described in detail in the third chapter, followed by results in the fourth chapter and discussion and conclusion in the fifth chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Mesiobuccal root of the maxillary first molar

The role of bacteria in the development of pulp and periapical disease is well established (Kakehashi *et al.* 1965). The goal of root canal treatment is either to prevent or eliminate microbial infection in the root canal system. Shaping and cleaning of all pulp spaces and the complete obturation of the canals with an inert filling material is necessary to achieve this objective. It is therefore important to have knowledge of internal anatomical relationships before undertaking root canal therapy.

Root canal morphology of teeth is often very complex and highly variable. Hess (1925) reported on the wide variation and complexity of root canal systems, such as fins and webbing. The author recognized that a root with a tapering canal and a single foramen was the exception rather than the rule. The mesiobuccal (MB) root of the maxillary first molar has generated more research and clinical investigation than any other root (Cleghorn *et al.* 2006). Several studies have been conducted on the canal configuration of this root in populations with different ethnic backgrounds (Weine *et al.* 1999, Alavi *et al.* 2002, Khraisat & Smadi 2007). The MB root with its broad bucco-palatal dimension and associated concavities on its mesial and distal surface is consistent with the majority of the MB roots having more than one canal while there is usually one canal in the distobuccal and palatal roots (Walton & Vertucci 2002).

In the literature, the reported incidence of second MB canals (MB2) in the MB root of maxillary first molars has varied considerably. The incidence varies primarily due to the method used in the study. Detection of MB2 in maxillary molars *in vivo* has been lower than that of *in vitro* reports. Some *in vivo* studies reported values as low as 18.6% (Hartwell & Bellizzi 1982), while others reported values as high as 77.2%

(Neaverth *et al.* 1987). Similarly, results from *in vitro* studies vary with reports of values in the range between 25% (Pecora *et al.* 1992) and 96.1% (Kulild & Peters 1990).

The use of new instrument designs, equipment and techniques (e.g. operating microscope, ultrasonic tips, staining the chamber floor, rhomboidal access) has resulted in an increased prevalence of the clinical detection of the MB2 canal (Vertucci 2005). Fogel *et al.* (1994) evaluated the use of 2.5x magnification telescopes and fiberoptic headlamps for additional illumination for locating MB2 canals in maxillary first molars *in vivo*. Access preparations were modified to a more rhomboidal shape to facilitate the search for the MB2. A groove was made on the floor of the pulp chamber lingual to the MB orifice, following the developmental groove between the MB and the palatal canal orifices. They found that 148 of 208 (71.2%) MB roots had 2 canals. Buhrley *et al.* (2002) also assessed the effect of magnification (microscopes and dental loupes) on the incidence of MB2 in another clinical study. The results of their study showed that the use of magnification leads to an MB2 detection rate three times more than that of the no magnification group and that the use of no magnification results in the location of significantly fewer MB2 canals.

Clinical studies on the MB root of the maxillary first molar

The clinical methods used to assess the MB root of maxillary first molars vary; some studies examined the root using patient records. Other studies used *in vivo* radiographs or clinically evaluated the root during endodontic treatment with or without magnification.

In a review of treatment records involving 714 maxillary first and second molars, Hartwell and Bellizi (1982) found a second MB canal in 18.6% of first molars and 9.6% of second molars. Some studies evaluated the frequency of MB2 canals clinically and in the laboratory and highlighted the clinical difficulty in locating second mesiobuccal canals. Seidberg *et al.* (1973) clinically evaluated 201 maxillary first

molars and reported that 33.3% of the teeth had two MB canals. This was about half of the result reported in the *in vitro* phase of their study of 100 teeth (62%). Similarly Pomeranz and Fishelberg (1974) compared *in vivo* versus *in vitro* techniques, and found a second MB canal in 28% of the maxillary first molar teeth studied clinically compared with 72% of the teeth that were decalcified *in vitro* and evaluated. The authors highlighted the importance of devoting clinical time to the location and treatment of the MB2 canal in the endodontic treatment of every maxillary molar.

Neaverth *et al.* (1987) evaluated 228 maxillary first molars clinically and found that they contained complicated root canal systems more frequently than what previous studies indicated. They found that 77.2% of MB roots have 2 canals. The authors also suggested that more attention should be directed toward searching for and locating the second canal in the MB root of maxillary molars.

Weller & Hartwell (1989) stated that there is a higher probability of finding the MB2 if the initial access is modified from the classical triangular shape to a more rhomboidal shape. They also advised that the developmental groove between the MB and palatal canals be explored to locate this fourth canal. In a retrospective study of 1134 maxillary molars treated using this technique the authors were able to locate 4 canals in 39% of maxillary first molars, and 21.4% of second molars. Wolcott *et al.* (2002) reported that there were significant differences in the incidence of locating the MB2 canal between initial treatments and retreatments and concluded that failure to find and treat existing MB2 canals decreases long-term prognosis.

In a clinical study that examined 1096 first maxillary molars, Stropko (1999) found MB2 canals in 73.2% of the teeth examined. However, the author reported that the percentage of MB2 canals located increased to 93.0% as the operator became more experienced, scheduled sufficient clinical time for treatment, routinely employed the operating microscope, and used specific instruments adapted for microendodontics. On the other hand, a study by Sempira & Hartwell (2000) found that the use of the

operating microscope did not increase the number of MB2 canals located. They reported that their stringent selection criteria were the cause for their lower percentage of second MB2 canals (33.1%) when compared with other studies. In their study, for the MB2 canal to be included, it had to be negotiated and obturated to within 4 mm of the apex.

Filho *et al.* (2009) investigated the internal morphology of maxillary first molars by 3 different methods: *ex vivo*, clinical, and cone beam computed tomography (CBCT) analysis. The *ex vivo* study evaluated 140 extracted maxillary first molars using an operating microscope. The clinical analysis used the records of 291 patients who had undergone endodontic treatment in a dental school during a 2-year period. The CBCT analysis evaluated 54 maxillary first molars. The *ex vivo* assessment results showed a fourth canal frequency in 67.14% of the teeth. Clinical assessment showed that 53.26% of the teeth exhibited 4 canals while CBCT results showed 4 canals in 37.05% of the teeth. The authors concluded that the maxillary first molar teeth showed significant variations in their root canals, and that the location and identification of the root canals were facilitated by using an operating microscope and CBCT. The authors also reported that because intraoral radiographs have been relatively inaccurate for the assessment of the presence of additional canals in maxillary molars, CBCT can be used as a good method for initial identification of maxillary first molar internal anatomy.

Laboratory studies on the MB root of the maxillary first molar

A wide variety of methods have been used in the laboratory studies evaluating the MB root of the first molar. These include clearing studies, injection of dye or ink, grinding or sectioning, plastic or metal castings, *in vitro* macroscopic examination, *in vitro* radiopaque gel infusion and radiography, *in vitro* radiography, CBCT, scanning electron microscope examination or micro-computed tomography (micro-CT) scanning.

The complexity of the MB root was first recognized in 1969. According to Weine *et al.* (1969), the first and second MB canals generally either merge 1-4 mm from the apex and exit with a common foramen, or remain separate and exit through two foramina. Pineda (1973) studied the morphology of the MB root of 245 extracted maxillary first molars using radiographs. The author reported that 40.8% of the roots had only one canal, 29.8% had 2 independent canals with two apical foramina, and 12.3% had two canals that merged apically and exited in a single foramen. About 7.3% had one canal that subsequently divided into two canals exiting through two separate foramina; 4.9% had 2 canals that merged into one and then bifurcated to exit through two foramina; and 4.9% demonstrated reticular canals (3 or more vertical canals are present with lateral interconnections).

Barker *et al.* (1974) used an epoxy resin injection technique to study the root canal form of more than 100 maxillary molars. The authors concluded that the MB root is the most complex root, with usually 2 canals intercommunicating, and with fork-like terminations. Vertucci (1984) decalcified 100 maxillary first molars, injected them with dye and cleared them to evaluate the root canals. He found that 55% of MB roots had 2 canals; 51% had lateral canals, 52% had transverse anastomoses between canals and 8% had apical deltas (defined as complex ramifications of branches of the pulp canal located near the anatomical apex with the main canal not being discernible (Verma & Love 2011)).

Kulild & Peters (1990) studied first and second maxillary molars, and located a second canal in the coronal half of 95.2% of the roots using different methods. Hand instruments located 54.2% of the canals. When the access was modified and a bur was used to carefully remove dentine from the pulp chamber floor (troughing), a further 31.3% were located. The authors found an additional 9.6% after sectioning the teeth and viewing with a measuring microscope. In a scanning electron microscope study of the MB root of maxillary first and second molars, Gilles & Reader (1990) found that 90% of first molars and 70% of second molars had 2 canals. Thomas *et al.*

(1993) concluded that the MB root was complex, with no apparent relationship between the type of canal system in the MB root and the type of canal orifice present.

In a laboratory study by Imura *et al.* (1998), graduate students treated MB2 canals in only 52% of extracted maxillary first molar teeth. The reported incidence of MB2 significantly increased to 80.9% after rendering the same roots transparent. Other *in vitro* studies reported higher chances of detecting the presence of MB2 canals utilizing the dental operating microscope (Baldassari-Cruz *et al.* 2002), and dentine removal under magnification using ultrasonics (Yoshioka *et al.* 2005, Alaçam *et al.* 2008). Even when magnification or dentine troughing techniques were used, the MB2 canal was not detected in 13% (Yoshioka *et al.* 2005) and 16.5% (Smadi & Khraisat 2007) of the teeth due to calcifications or because of the canal's anatomy with branching located more apically.

Inter-canal communications in the MB root of the maxillary first molar

An inter-canal communication is defined as a branch of the pulpal space that runs between the main canals but does not communicate with the root surface (Verma & Love 2011). The literature often uses the term 'isthmus' to mean the same as inter-canal communication. This is because most of the studies used histological cross-sections to see the connection between the two canals and the usual appearance in this view is an isthmus. An isthmus has been defined as a narrow, ribbon-shaped communication between two root canals that contains pulp or tissue derived from the pulp (Weller *et al.* 1995). An isthmus is also known as a corridor (Green 1973), a lateral interconnection (Pineda 1973) or a transverse anastomosis (Vertucci 1984). Any root that contains two or more root canals has the potential to contain an inter-canal communication which can function as a bacterial reservoir. This becomes a significant factor in the thorough debridement of the root canal system. As mechanical cleaning and shaping of a canal communication is difficult and ineffective, it must be considered in failures following conventional orthograde root

canal treatment. In the study by Senia *et al.* (1971), the authors reported that the only way to clean such anatomic variations is through the use of chemical irrigants such as sodium hypochlorite. Even with the use of high concentrations of sodium hypochlorite and mechanical instrumentation, the amount of tissue dissolution was significantly limited.

This vitally important area must also be considered in failures of traditional endodontic surgery. Cambruzzi & Marshall (1983) were the first to highlight the significance of inter-canal communications in molar surgery, and stressed the importance of preparing and filling them. The authors advocated the *in vivo* use of methylene blue dye as an aid in visualizing the outline of the resected root surface and the presence of an inter-canal communication.

The actual formation of an 'isthmus' from embryonic origin is through the epithelial root sheath (Hsu & Kim 1997). It is suggested that if the epithelial cell is defective, an odontoblast does not differentiate and so no dentine formation occurs. If dentine formation does not occur, cementum is not deposited in the area. This condition leads to accessory [defined as any branch of the main pulp canal or chamber that communicates with the external surface of the root (Vertucci 2005)] and lateral [defined as accessory canals located in the coronal or middle third of the root (Vertucci 2005)] canals in teeth with single roots (Hsu & Kim 1997). In multi-rooted teeth and roots with multiple canals, the mechanism of root formation is similar to a single root trunk except at the cervical area where the root divides in the 'furcation zone'. Tongue-like projections of the epithelial root sheath develop and proliferate until fusion with other projections occurs. These epithelial projections then continue to proliferate and divide. In multi-rooted teeth, defects in the epithelial root sheath occur in a higher incidence than in single rooted teeth. If defects occur, these projections do not completely fuse with one another, forming lateral and accessory canals. If the projections completely fuse with one another, one root with one root canal system forms as in the distobuccal root of maxillary molars. If partial fusion

occurs then two root canals result, with inter-canal communications forming in between, such as the mesial root of mandibular first molars. If no fusion occurs then a large ribbon-shaped canal results, that also forms an isthmus throughout the entire root, as seen in some distal roots of mandibular first molars (Hsu & Kim 1997).

The incidence of inter-canal communications in the MB root of the maxillary first molar varies. Pineda (1973) reported interconnections in 4.9% of 245 roots examined. Other studies reported higher values; 16% (Green 1973), 30.1% (Cambruzzi & Marshall 1983), 37.11% (Khraisat & Smadi 2007) and values higher than 50% (Vertucci 1984, Somma *et al.* 2009, Verma & Love 2011). Vertucci (1984) reported that 10% of the anastomoses were located in the cervical third of the MB root, 75% were in the middle third and 15% were in the apical third of the root. Similarly, Khraisat & Smadi (2007) and Verma & Love (2011) reported that the inter-canal connections were mainly in the middle third of the root.

Hsu & Kim (1997) examined the incidence and position of canal isthmuses on maxillary and mandibular premolars as well as molars. Transverse serial sections of the root were prepared in 1 mm increments in the last apical 6 mm of the root. Using methylene blue dye, the apical side of each section was stained and viewed under a surgical operating microscope. In the MB root of the maxillary first molar, 60% of the root had 2 canals. The incidence of an isthmus was highest in the apical 3-5mm levels. In teeth that had 2 canals, the 4 mm sections contained an isthmus 100% of the time.

The concept of a partial isthmus was introduced in the study by Weller *et al.* (1995). Transverse serial sections of the apical 6 mm of MB roots of maxillary first molars were viewed with a surgical operating microscope. A complete isthmus had a continuous opening between the two main root canals. A partial isthmus was classified as a narrow projection of one root canal opening towards the second in the same root section but not joining. Weller *et al.* (1995) reported that the highest

incidence of isthmuses was again in the 3-5 mm from the root apex. The 4 mm level contained a complete isthmus 12% and a partial isthmus 88% of the time for a combined total of 100%. The presence of a partial isthmus was also reported by Teixeira *et al.* (2003). In the latter study, 70% of the MB roots of maxillary first molars had one canal, and 30% had two canals. Of the isthmuses present in the roots having 2 canals, 17.3% were complete and 11.7% were partial isthmuses.

Tam & Yu (2002) examined root sections of the MB root of maxillary first molars using a scanning electron microscope, and found that 31.25% of the roots with 2 canals contained either a complete isthmus or accessory canals or both, and 31.25% showed partial isthmus formation. The authors explained the concept of partial isthmus formation. In such areas, the cross-section of the canal is similar in shape to a comma. The tail extension of the canal may occur in several ways. First, it may be part of the fin or loop of the root canal. Second, the root may be sectioned at the point where one canal starts to twist and turn to join with the second canal. Third, it may be a true partial isthmus with a complete isthmus formed elsewhere in the root.

Hsu & Kim (1997) identified five types of isthmuses which can occur on a bevelled root surface: type (I) occurs when two or three canals are present with no connections in between, type (II) occurs when two canals are present with a definite connection between them, type (III) occurs when three canals are present with a definite connection between them, type (IV) occurs when canals extend into the isthmus area, and type (V) occurs when a true connection or corridor is present throughout the section (Fig. 2.1). Identification and treatment of isthmuses is vitally important for the success of surgical procedures.

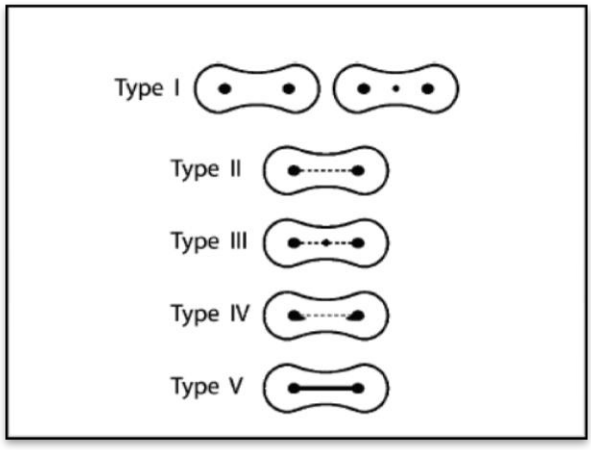


Figure 2.1 Types of canal isthmuses (from Hsu & Kim 1997).

A study by von Arx (2005) showed that a type (II) canal isthmus prevailed in the MB root of maxillary first molars. In this study, 56 mandibular and 32 maxillary first molars were subjected to periradicular surgery. The high incidence of canal isthmuses in MB roots of maxillary first molars described in *in vitro* studies was confirmed, with 76% of resected MB roots having 2 canals and an isthmus, 10% having 2 canals and no isthmus, and 14% having a single canal. Endoscopic inspection of the cut root faces demonstrated that none of the isthmuses were filled, emphasizing the difficulty of orthograde instrumentation and root filling of canal isthmuses. Jung *et al.* (2005a) investigated the prevalence and location of anatomical variations (accessory root canals and isthmuses) in the apical anatomy in MB roots of maxillary first molars and mesial roots of mandibular molars after instrumentation. The authors found that anatomical variations persisted following instrumentation and concluded that these variations should be considered during surgical or nonsurgical endodontic procedures of permanent first molars.

Inter-canal communications were also evaluated in a study by Verma & Love (2011) using micro-CT. The authors confirmed that the morphology of the MB root of maxillary first molars is complex with a MB2 canal present in 90% of the roots examined. Inter-canal communications were present in 55% of the roots. A high percentage (85%) of the roots had accessory canals and 40% had apical deltas. Inter-

canal communications were found in all areas of the roots: In the apical area (45%), the authors described the communications as narrow bands, running from the main canal to another. In the coronal (36%) and middle (73%) areas of the root, inter-canal communications were described as either narrow bands running from one canal to another, leading to formation of loops or two canals joining to form one band, which again divided into two.

Somma *et al.* (2009) considered isthmuses and inter-canal connections as separate entities. The authors analyzed micro-CT images and identified an isthmus when the two canals appeared as a single ribbon shaped canal on several consecutive cross-sections. They identified an inter-canal connection as an accessory pulp space commencing from a root canal in one cross-section that entered the other root canal in other cross-sections. Somma *et al.* (2009) reported that inter-canal connections between two canals were found in all specimens, with isthmuses in 71% of the cases. The authors confirmed that the MB root of the maxillary first molar has a complex canal anatomy.

The above review of the studies highlights the complexity of the root canal anatomy of the MB root of the maxillary first molar. Variations in canal morphology such as extra canals, apical deltas, fins, webbing, inter-canal communications, or lateral and accessory canals are commonly encountered. Inability to find and properly debride root canals may cause failures of root canal treatments, therefore knowledge of these variations when treating canals is essential for the success of endodontic therapy.

2.2 Mechanical root canal preparation

The preparation of the root canal system is one of the most important stages in root canal treatment (Schilder 1974). Since the presence of bacteria is the key factor in the development of pulp inflammation and apical periodontitis (Kakehashi *et al.* 1965), root canal treatment is directed towards the elimination of bacteria and their substrates from the pulp and canal space. Root canal preparation therefore involves

the removal of necrotic or infected pulp and tissue debris, removal of inflamed pulp, removal of vital healthy pulp in cases of elective treatment, and in cases of retreatment, the removal of metallic and non-metallic obstacles. Mechanical preparation and chemical disinfection of the canal cannot be considered separately and hence this step in root canal treatment is often referred to as chemomechanical debridement or biomechanical preparation of the root canal system. This section will review the mechanical aspects of root canal preparation.

Mechanical preparation debrides infected canal contents and radicular dentine, creates the space to facilitate disinfection of the canal by irrigants and canal medicaments and provides the shape for placement of the root canal filling. In the literature many terms have been used to refer to this step. These include instrumentation, preparation, enlargement, and shaping.

Peters (2004) described three main issues that are challenging and controversial in root canal preparation. These are: 1) locating, accessing and enlarging canals without procedural errors, 2) maintaining working length, 3) selection of the right instruments' size and geometry for preparation of canals with adequate disinfection and subsequent obturation.

Increased awareness of the complexities of the root canal system has led to the development of new techniques, instruments and materials which greatly enhance clinicians' abilities to achieve the goals of root canal treatment. Techniques for root canal preparation include mechanical preparation (manual preparation, automated root canal preparation, sonic and ultrasonic preparation) and other experimental nontraditional techniques including laser systems (Weichman & Johnson 1971) or non-instrumental devices (Lussi *et al.* 1993). Nontraditional techniques however are not readily available at present, therefore cleaning and shaping root canals will continue to include mechanical preparation for the near future.

Ingle (1961) described the 'standardized technique' for root canal preparation, designed for single-cone filling techniques. In this technique, each instrument was introduced to working length, resulting in a canal shape that matched the taper and size of the final instrument. Later, and with the increased popularity of gutta-percha as the root filling material, Schilder (1974) recommended that the basic shape of the canal should be a continuously tapered funnel following the original shape of the canal.

Schilder (1974) described five design objectives for canals to be filled with gutta-percha. These are: 1) the shape should be a continuously tapered funnel from apex to access cavity, 2) cross-sectional diameters should be narrower as we move apically, 3) the shape of the original canal should be maintained, 4) the original position of the apical foramen should be maintained, and 5) the apical opening should be kept as small as practical. Four important biological objectives were also described: 1) confinement of the preparation to the roots themselves, 2) avoidance of further irritation or infection of the periradicular tissues from necrotic debris forced beyond the foramina, 3) removal of all tissue, vital and necrotic, from the main root canal, and 4) creating sufficient space for intracanal medicaments and irrigation. These objectives are still considered in today's mechanical preparation of root canals.

Nickel-titanium instruments

The introduction of nickel-titanium (NiTi) alloy to endodontic instrument design added new dimensions to the practice of endodontics (Walia *et al.* 1988). Two of the main characteristics of this alloy are shape memory and superior elasticity. Alloys like NiTi undergo a stress-induced martensitic transformation from a parent structure, which is austenite. When the stress is released, the alloy returns back to the austenite phase, recovering its original shape in the process. The super-elasticity property of NiTi, and its ability to return to its original shape following significant deformation, differentiates it from other metals, such as stainless steel (SS), which

sustain deformation and retain permanent shape change. The elastic limit of NiTi in bending and torsion is two to three times higher than that of SS instruments. These properties make NiTi endodontic files more flexible and better able to conform to canal curvature, resist fracture and wear less than SS files.

Walia *et al.* (1988) reported superior results with NiTi files in bending and torsion compared to SS hand files of the same size manufactured by a similar machining process. Subsequently, many manufacturers began to market NiTi endodontic instruments in the 1990s. NiTi instruments offer new perspectives for root canal preparation that have the potential to avoid some of the major drawbacks of traditional instruments and devices (Pettiette *et al.* 1999). They stay more centered in the canal, produce rounder preparations, and reduce procedural accidents, such as transportation and ledging (Glosson *et al.* 1995). This in turn may result in better clinical outcomes (Pettiette *et al.* 2001).

For a true comparison of clinically relevant qualities of instruments manufactured from different alloys, the instruments must be identical in design (Kazemi *et al.* 2000). Schäfer & Lau (1999) compared hand NiTi files with SS files of the same cross-sectional geometry under standardized experimental conditions and found that the NiTi files removed less material than the SS files. In many studies that compared SS hand filing with either NiTi hand filing or NiTi rotary files, there was significantly less transportation of the canal system with the NiTi files (Shadid *et al.* 1998, Song *et al.* 2004, Guelzow *et al.* 2005, Taşdemir *et al.* 2005, Schirrmeister *et al.* 2006). A study using high resolution computed tomography found that the NiTi ProFile system (Dentsply Maillefer, Ballaigues, Switzerland) transported the most when compared with SS hand files or LightSpeed (LightSpeed, Inc., San Antonio, TX) rotary NiTi files (Peters *et al.* 2001a). There is however, a general acceptance that rotary NiTi instruments produce well-shaped canals in an efficient manner with the creation of fewer iatrogenic problems than SS files.

Instrumentation of the root canal system in most instances requires hand (to establish a glide path) and rotary files. No canal system should be instrumented with rotary files alone. When hand NiTi filing was compared with rotary NiTi filing, there were no significant differences in canal transportation (Deplazes *et al.* 2001, Peters *et al.* 2001b, Kaptan *et al.* 2005). Most manufacturers of rotary files recommend a strict crown-down technique for canal preparation mainly to avoid overloading rotating instruments with large frictional wall contact (Blum *et al.* 1999). This is believed to reduce the incidence of file fracture, in particular torsional fracture (Sattapan *et al.* 2000, Roland *et al.* 2002). In the crown-down technique, larger files are used first in the coronal two-thirds of the canals and then progressively smaller files are used more apically. This allows apical progression of the instrument by elimination of coronal interferences with the preceding instrument (Morgan & Montgomery 1984). This technique also decreases the deviation of instruments in canal curvatures by reducing root wall contact and decreases canal blockages because of removal of tissue debris coronally thereby minimizing the chances of pushing debris apically. Recently, other instruments have appeared on the market that are to be used in a single-length technique, similar to the standardized technique for hand instruments. Apical enlargement is sometimes then done after crown-down has been accomplished. At this stage, different techniques are possible by switching tapers or tip sizes and changing to different instruments.

There have been three different handling recommendations described for the use of rotary instruments. The first recommendation is to use the rotating file with very slight apical pressure, until the instrument stalls, and then to immediately withdraw the file (Buchanan 2000). At this point, the file has done its cutting action and the flutes are loaded with debris that must be removed. The file is then reinserted. This movement has been recommended for RaCe files (FKG, La Chaux-de-Fonds, Switzerland), designed to avoid threading into the canal. The second recommendation for most other rotary instruments is to use them in an up-and-

down movement (Li *et al.* 2002, Barbakow 2004), with a very light touch to avoid taper lock and to distribute forces throughout the canal. Taper lock occurs when the shape of the tapered root canal being prepared becomes similar to the instrument in use (Yared *et al.* 2001, 2002). Instruments may then become locked into the canal, and the tip may fracture (Sattapan *et al.* 2000). This movement is continued until a certain resistance is met or working length is reached. The third recommendation is to use the instrument in a "brushing" motion (Ruddle 2005). The file is moved laterally instead of inserting it axially in the canal in order to avoid threading in. This movement is recommended for files such as ProTaper instruments (Dentsply Maillefer, Ballaigues, Switzerland).

Criteria for assessment of the quality of root canal preparation

Most studies that evaluated canal preparation techniques have been conducted *in vitro*. When analyzing the quality of root canal preparation created by instruments and techniques several parameters can be considered, including their cleaning ability as observed using histological sectioning (Walton 1976) or the scanning electron microscope (Mizrahi *et al.* 1975, Hülsmann *et al.* 1997). Other parameters include their shaping ability (Gambill *et al.* 1996, Kosa *et al.* 1999), safety issues (Al-Omari & Dummer 1995), working time, handling and cost.

The aim of studies analyzing post-operative root canal shape is to evaluate the conicity, taper and flow of the prepared root canal, and maintenance of the original canal shape. The ability of an instrument or a technique to allow the prepared canal to stay centered is seen as a positive aspect. Conversely, canal transportation and preparation errors are seen as a negative aspect. Canal transportation can be defined as any undesirable deviation from the natural canal path (Peters 2004). The formation of preparation errors, for example zip and elbow formation, ledges, strip-perforations, or excessive thinning of canal walls are possible results of canal transportation (Peters 2004). It is believed that these errors are due to the interaction

of canal curvature, file design, and file handling. The tendency of a file to straighten itself cannot be completely overcome by pre-curving and leads to uneven distribution of forces and hence material removal (Weine *et al.* 1975). In a curved canal, apical pressure leads to transportation toward the outer curvature. At the same time, the reactionary force builds up in the straightening instrument against the dentine coronal of the curvature and leads to transportation toward the inner curvature (Weine *et al.* 1975). Canal transportation could result in inadequate preparation and disinfection, with the possible outcome of failed endodontic treatment and persisting apical lesions, or in thinned canal walls that could result in perforations or vertical fractures.

Some studies have shown that there was no significant difference in canal transportation when various rotary instruments were compared with each other; Hero 642 (Micro-Mega, Besancon, France) versus Quantec SC (Analytic Endodontics, Glendora, CA) (Hülsmann *et al.* 2001), ProTaper (Dentsply Maillefer) versus K3 (SybronEndo, West Collins, CA) (Bergmans *et al.* 2003), Flexmaster (VDW, Munich, Germany) versus Hero 642 (Hülsmann *et al.* 2003a). Other studies, however, showed a significant difference when other systems were compared. There was significantly more transportation at 4 mm from the working length with ProFile Series 29 (Dentsply Tulsa Dental, USA) when compared with ProTaper (Dentsply Maillefer) (Iqbal *et al.* 2004). In contrast, ProFile instruments (Dentsply Maillefer) showed significantly less transportation than K3 files (SybronEndo) depending on canal curvature (Ayar & Love 2004). When ProTaper (Dentsply Maillefer) was compared with RaCe (FKG), less transportation occurred with RaCe instruments (Schäfer & Vlassis 2004b). Another study however compared ProTaper (Dentsply Maillefer) and RaCe (FKG) and found no significant differences for canal straightening or canal shape (Paqué *et al.* 2005b). Table 2.2 summarizes some of the studies on various NiTi instruments evaluating canal shape after preparation.

Preparation of canals may be evaluated using extracted teeth or simulated root canals in resin blocks. The major advantage of the use of extracted human teeth is the reproduction of the clinical situation. The use of extracted teeth, however, makes it difficult to standardize variables such as root canal length and width, dentine hardness, calcifications, and the location and the nature of canal curvatures. Simulated root canals have the advantages of standardization of the degree, site and radius of root curvature in three-dimensions, as well as the 'tissue' hardness and width of the canals (Dummer *et al.* 1989, 1991). Pre- and post-instrumentation outlines of a canal can be superimposed and any changes in shape can be evaluated using the appropriate computer software or subtraction radiography. This technique evaluates the root canal curvature and the subsequent straightening during preparation only in one direction at a time. Simulated canals do not simulate the coinciding bucco-lingual and mesio-distal curvatures often found in natural teeth (Cunningham & Senia 1992). Some studies showed that the results regarding canal straightening from simulated root canals do not differ from those from extracted teeth (Lim & Webber 1985, Ahmad 1989). The frictional heat generated by rotary instruments however may be sufficient to melt some resins and therefore this model may not be suitable in all cases. Furthermore, resin lacks the material qualities of human dentine. Resin is less hard and more compressible than root dentine, and as a result the removal of dentine requires twice the force that needs to be applied for resin (Lim & Webber 1985). In addition, resin debris formed during preparation of simulated root canals is not as fine as dentine debris, and tends to tangle which may result in frequent blockages of the apical portions and difficulties in clearing it in resin canals (Lim & Webber 1985). Therefore, caution should be exercised in the interpretation of results from resin blocks (Thompson & Dummer 1997a).

Other methodologies have been described to evaluate endodontic instrumentation, including superimposing radiographs before and after shaping (Luiten *et al.* 1995), silicone impressions of instrumented canals and photographic assessment (Abou-

Rass & Jastrab 1982, Barthel *et al.* 1999), and computer manipulation for comparative analysis (Tucker *et al.* 1997, Porto Carvalho *et al.* 1999).

One of the most popular methods of evaluation of canal shapes is the *in vitro* 'muffle system'. Bramante *et al.* (1987) were the first to develop this method to evaluate changes in canal diameters. In that study, extracted teeth were embedded in acrylic resin blocks and a plaster muffle was constructed around the resin block. The specially designed mould allowed sectioning of the root, removal, and precise repositioning of the resulting root disks for instrumentation. Pre- and post-instrumentation photographs of the root canal diameter were superimposed and deviations between the two root canal outlines were measured. A key advantage of this technique is that data can be gathered both pre- and post-instrumentation, and differences in measurements can be compared. The Bramante technique was later modified in other studies (McCann *et al.* 1990a, Kuttler *et al.* 2001). Disadvantages of this technique include loss of material due to serial sectioning, the samples need a lot of preparation, and not all sections are at right angles to the main canal. The quantification of post-instrumentation root canal deviation may be performed using a 'centering ratio' method (Calhoun & Montgomery 1988, Leseberg & Montgomery 1991, Gambill *et al.* 1996, Kosa *et al.* 1999), or from modified formulas (Portenier *et al.* 1998, Deplazes *et al.* 2001) or by measurements of the pre- and post-instrumentation dentine thickness (McCann *et al.* 1990b), or directly from the Pythagorean theorem (Coleman & Svec 1997, Short *et al.* 1997, Shadid *et al.* 1998).

Finally, a non-destructive technology; micro-computed tomography (micro-CT), has been described for the comparison of pre- and post-instrumentation images. This new technique allows three-dimensional replication of the canal system, pre- and post-instrumentation. A detailed review of micro-CT follows in section 2.3.

Table 2.2 Summary of studies that evaluated shaping abilities of various NiTi files

File Systems	Year	Method	Result	Reference
Mac-Files, hand & rotary files	1995	Extracted teeth (superimposing radiographs)	NiTi files significantly more effective than SS (K-flex files)	(Esposito & Cunningham 1995)
LightSpeed, Mity hand, NT sensor files & Canal Master U hand	1995	Extracted teeth (modified Bramante technique & computer software)	LightSpeed superior to Mity files	(Glosson *et al.* 1995)
NiTi K-files versus SS K-files	1996	Resin blocks (Bramante technique & computer software)	NiTi significantly less transportation, minimal straightening	(Coleman *et al.* 1996)
ProFile 0.04 Series 29	1996	Resin blocks (photographic technique)	NiTi superior to ultrasonics & K-files	(Zmener & Banegas 1996)
NiTi K-files versus SS K-files	1996	Extracted teeth (modified Bramante technique & computer software)	NiTi superior to SS	(Chan & Cheung 1996)
LightSpeed	1996	Extracted teeth (radiographic technique)	Little/no transportation	(Knowles *et al.* 1996)
LightSpeed	1996	Resin blocks (radiographic technique)	Superior to K-files	(Tharuni *et al.* 1996)
NiTi K-files versus SS K-files	1996	Extracted teeth (computed tomography)	NiTi superior to SS K-files	(Gambill *et al.* 1996)
ProFile 0.04 Taper Series 29, McXIM & LightSpeed	1997	Extracted teeth (modified Bramante technique & computer software)	All NiTi systems superior to SS hand files	(Short *et al.* 1997)
NT Engine, McXim	1997	Resin blocks (video images & computer software)	Minimal transportation	(Thompson & Dummer 1997e)
LightSpeed	1997	Resin blocks (video images & computer software)	Minimal transportation	(Thompson & Dummer 1997c,1997d)

ProFile 0.04 Taper Series 29	1997	Resin blocks (video images & computer software)	Little transportation	(Thompson & Dummer 1997a,1997b)
NiTi K-files versus SS K-files	1997	Resin blocks (Bramante technique & computer software)	NiTi less transportation	(Coleman & Svec 1997)
LightSpeed	1998	Extracted teeth (Bramante technique & photographic technique)	Superior to Flex-R	(Shadid *et al.* 1998)
Quantec Series 2000	1998	Resin blocks (video images & computer software)	Relatively large number of aberrations including four perforations	(Thompson & Dummer 1998a,1998b)
ProFile 0.04 with ISO tips	1998	Resin blocks (computer software)	24% zips & elbows formation, little straightening	(Bryant *et al.* 1998a,1998b)
Mity Roto 360°, Naviflex	1998	Resin blocks (video images & computer software)	High incidence of ledges, little straightening	(Thompson & Dummer 1998c)
ProFile 0.04 & 0.06	1998	Extracted teeth (radiographic technique)	No difference, little or no transportation	(Kavanagh & Lumley 1998)
ProFile 0.04 & 0.06 combined	1999	Resin blocks (image analysis software)	Good canal shapes, little straightening	(Bryant *et al.* 1999)
Naviflex & ProFile 0.04	1999	Extracted teeth (Bramante technique & photographic technique)	No difference, little transportation	(Ottosen *et al.* 1999)
Hero 642	2000	Resin blocks (video images & computer software)	Few aberrations, inadequate taper	(Thompson & Dummer 2000)
Quantec LX	2000	Resin blocks (image analysis software)	>50% outer widening	(Griffiths *et al.* 2000)
ProFile 0.04, 0.06, ProFile GT Rotary	2000	Resin blocks (digitized images & analysis software)	NiTi superior to K-Flex	(Kum *et al.* 2000)

NiTiFlex & ProFile 0.04	2000	Extracted teeth (micro-CT)	No difference, well centered & tapered shapes	(Rhodes *et al.* 2000)
Hero 642 versus Quantec SC	2001	Extracted teeth (modified Bramante technique & radiographic technique)	No difference, little or no transportation	(Hülsmann *et al.* 2001)
Hero 642	2001	Extracted teeth (Bramante technique & image analysis software)	Little transportation, superior to SS files	(Bertrand *et al.* 2001)
Quantec SC	2001	Resin blocks (image analysis software)	Severe aberrations after instrumentation to size 25, 0.05 taper	(Griffiths *et al.* 2001)
LightSpeed, ProFile 0.04	2001	Extracted teeth (micro-CT)	Little transportation	(Peters *et al.* 2001a)
NiTi K-files, LightSpeed, ProFile 0.04 & GT Rotary instruments	2001	Extracted teeth (micro-CT)	Few differences, all techniques left 35% or more of canal surface area unchanged	(Peters *et al.* 2001b)
GT Rotary versus Flexofiles	2001	Extracted teeth (high resolution computed tomography)	Little transportation, superior to Flexofiles	(Gluskin *et al.* 2001)
NiTi FlexMaster versus SS K-Flexofile	2002	Resin blocks (computer image analysis software)	Minimal transportation, superior to K-Flexofiles	(Schäfer & Lohmann 2002a)
NiTi FlexMaster versus SS K-Flexofile	2002	Extracted teeth (computer image analysis software)	FlexMaster superior to K-Flexofiles	(Schäfer & Lohmann 2002b)
LightSpeed versus GT Rotary	2002	Extracted teeth (micro-CT)	No difference, little transportation	(Bergmans *et al.* 2002)
ProFile 0.04 versus LightSpeed	2002	Extracted teeth (modified Bramante technique, photographic & radiographic technique	No difference, little or no transportation	(Versümer *et al.* 2002)
GT Rotary	2002	Resin blocks (image analysis system)	Little transportation	(Calberson *et al.* 2002)

FlexMaster versus Hero 642	2003	Extracted teeth (modified Bramante technique & radiographic technique)	No difference, little or no transportation	(Hülsmann *et al.* 2003a)
LightSpeed versus Quantec SC	2003	Extracted teeth (modified Bramante technique & radiographic technique)	No difference, little or no transportation	(Hülsmann *et al.* 2003b)
ProTaper versus K3	2003	Extracted teeth (micro-CT)	Little transportation	(Bergmans *et al.* 2003)
ProTaper	2003	Extracted teeth (micro-CT)	Little transportation	(Peters *et al.* 2003a)
K3	2003	Resin blocks (computer image analysis software)	Little transportation, superior to K-Flexofiles	(Schäfer & Florek 2003)
K3	2003	Extracted teeth (computer image analysis software)	Little transportation, superior to K-Flexofiles	(Schäfer & Schlingemann 2003)
FlexMaster	2003	Extracted teeth (micro-CT)	Little transportation	(Hübscher *et al.* 2003)
FlexMaster versus LightSpeed & NiTi hand	2003	Extracted teeth (Bramante technique & photographic technique)	Little transportation, LightSpeed superior to FlexMaster	(Weiger *et al.* 2003)
ProTaper versus ProFile series 29	2004	Extracted teeth (radiographic technique)	Systems comparable to each other	(Iqbal *et al.* 2004)
ProTaper versus RaCe	2004	Resin blocks (computer image analysis software)	RaCe superior to ProTaper	(Schäfer & Vlassis 2004a)
ProTaper versus RaCe	2004	Extracted teeth (computer image analysis software)	RaCe significantly superior to ProTaper	(Schäfer & Vlassis 2004b)
FlexMaster versus SS & NiTi hand	2004	Clinical study	Minimal straightening with FlexMaster	(Schäfer *et al.* 2004)
GT Rotary versus ProTaper	2004	Extracted teeth (radiographic technique)	No difference, little or no transportation	(Veltri *et al.* 2004)

ProFile 0.06 versus K3 0.06	2004	Resin blocks (digital images & computer analysis software)	Minimal canal transportation, ProFile significantly less transportation than K3	(Ayar & Love 2004)
RaCe	2005	Resin blocks (computer image analysis software)	Few aberrations	(Rangel *et al.* 2005)
RaCe versus ProTaper	2005	Extracted teeth (modified Bramante technique & radiographic technique)	No difference, little or no transportation	(Paqué *et al.* 2005b)
FlexMaster, System GT, Hero 642, K3, ProTaper & RaCe	2005	Extracted teeth (Bramante technique, radiographic technique, computer analysis, light-microscopic and photographic documentation)	Minimal straightening, no difference between systems	(Guelzow *et al.* 2005)
Hero 642	2005	Extracted teeth (computed tomography)	Hero 642 superior to SS K-files	(Taşdemir *et al.* 2005)
RaCe versus FlexMaster	2006	Resin blocks (image analysis software)	Few aberrations in both systems	(Merrett *et al.* 2006)
FlexMaster, GT Rotary, ProFile, ProTaper & RaCe	2006	Resin blocks (image analysis software)	RaCe superior to other instruments	(Schirrmeister *et al.* 2006)
Mtwo versus K3 & RaCe	2006	Resin blocks (computer image analysis software)	Mtwo superior to K3 & RaCe	(Schäfer *et al.* 2006a)
Mtwo versus K3 & RaCe	2006	Extracted teeth (computer image analysis software)	Mtwo significantly better than K3 & RaCe	(Schäfer *et al.* 2006b)
NiTi-Tee versus K3	2006	Extracted teeth (modified Bramante technique & radiographic technique)	Minimal straightening in both systems	(Jodway & Hülsmann 2006)
HeroShaper, ProTaper & RaCe	2006	Extracted teeth (computed tomography)	RaCe significantly transported at coronal level	(Uyanik *et al.* 2006)

Sequence & Liberator versus SS Flex-R	2007	Extracted teeth (radiographic technique)	No significant difference in apical canal transportation	(Matwychuk *et al.* 2007)
Hero 642, Hero Shaper & Hero Apical	2007	Extracted teeth (stereoscopic magnifier & computer analysis)	Deviations present in all instruments	(Câmara *et al.* 2007)
ProTaper, Hero 642 & ProTaper + Hero 642	2008	Resin blocks (computer image analysis software)	ProTaper + Hero 642 superior to ProTaper or Hero 642	(Zhang *et al.* 2008)
Alpha System versus ProTaper Universal	2009	Extracted teeth (modified Bramante technique & radiographic technique)	Significantly less apical straightening with Alpha System	(Vaudt *et al.* 2009)
ProTaper, Mtwo, BioRaCe & BioRaCe + S-Apex	2009	Resin blocks (image analysis software)	BioRaCe + S-Apex superior to other systems	(Bonaccorso *et al.* 2009)
RaCe	2009	Extracted teeth (cone beam computed tomography)	Minimal canal transportation, adequate centering ability	(Pasternak-Junior *et al.* 2009)
Self-adjusting File	2010	Extracted teeth (micro-CT)	Little canal surface uninstrumented	(Peters *et al.* 2010)
Self-adjusting File	2011	Extracted teeth (micro-CT)	Little canal transportation	(Peters & Paqué 2011)

Rotary instrument design

Manufacturers of NiTi rotary files continue to design and introduce new systems with different characteristics in tip sizing, taper, cross-section, helical angle, and pitch. These different designs may influence instruments' flexibility, cutting efficacy, and torsional resistance. Some of the early systems have been removed from the market today, whereas other systems such as ProFile (Dentsply Maillefer) are still widely used. The rapid succession of new development is at least partly the reason for the few clinical outcome studies at this point. Peters *et al.* (2004) analyzed clinical results of endodontic treatment performed with three NiTi rotary preparation techniques and found that outcome is significantly affected by preoperative diagnosis but not by the specific choice of instrumentation system. The differences in clinical outcomes in regard to design variations appear to be minimal (Schäfer *et al.* 2004, Guelzow *et al.* 2005). *In vitro* tests have only begun to identify the effect of specific designs on shaping outcomes (Hülsmann *et al.* 2005).

File design is essential in avoiding preparation errors. The design of the instrument tip in particular has been identified as a potential factor for shaping outcomes (Powell *et al.* 1986, Dummer *et al.* 1998, Hülsmann *et al.* 2001); with preparation errors being linked to file designs with sharp tips (Powell *et al.* 1986, Dummer *et al.* 1998). Instruments with actively cutting tips such as Quantec SC (Analytic Endodontics) (Griffiths *et al.* 2001) and Quantec LX (Analytic Endodontics) (Griffiths *et al.* 2000) produced more aberrations than instruments with non-cutting tips such as ProFile 0.04 and 0.06 tapers (Dentsply Maillefer) (Bryant *et al.* 1998a, 1998b, 1999, Kum *et al.* 2000) and LightSpeed (LightSpeed Inc.) (Thompson & Dummer 1997c, 1997d). On the other hand, shaft design has a lesser effect (Versiani *et al.* 2008). Studies have shown that shaft design, whether smooth flexible versus active tapered (Bergmans *et al.* 2002), or progressive versus constant tapered (Bergmans *et al.* 2003), did not significantly modify canal shapes prepared to similar apical sizes. Although it is generally held that a thin flexible shaft allows larger apical shapes with less

aberrations (Portenier *et al.* 1998, Card *et al.* 2002), Hata *et al.* (2002) found that apical transportation caused by a combination of ProFile 0.04 and 0.06 (Dentsply Maillefer) was less than that of ProFile 0.04 instruments alone.

The design of the cutting blade has undergone modification from passive 'U-file' designs (radial lands) in instruments such as ProFile (Dentsply Maillefer), GT File (Dentsply Tulsa Dental, USA) and LightSpeed files (LightSpeed Inc.) to more actively cutting triangular designs in instruments such as ProTaper (Dentsply Maillefer), FlexMaster (VDW), K3 (SybronEndo), Hero 642 (Micro-Mega) and RaCe (FKG). The Mtwo (Sweden & Martina, Padova, Italy) cross-sectional design resembles that of a S-shaped file with 2 blades (Bonaccorso *et al.* 2009). Pentagon and kite-shaped cross-section designs were also introduced. However, while there is only limited evidence for each individual file (Schäfer 2001, Hübscher *et al.* 2003, Schäfer & Schlingemann 2003, Peters *et al.* 2003b), the introduction of actively cutting cross-sections does not appear to negatively affect centering abilities. It is thought that radial lands tend to burnish the cut dentine onto the root canal wall or may push debris inside the dentinal tubules, whereas active cutting edges seem to cut and remove both dentine chips and pulp remnants (Hülsmann *et al.* 2005, Schäfer & Oitzinger 2008). Active cutting blades however, should not be taken beyond the apical constriction or allowed to linger apically to avoid the occurrence of canal transportation. On the other hand, radial-landed instruments, even when accidentally taken beyond the apical foramen, will not engage and create an apical zip formation due to the passive reaming action (Lloyd 2005).

BioRaCe instruments

In 1999, 10 years after the first NiTi instruments were introduced, the RaCe system (FKG) became available (Baumann 2005). Recently, a new system, BioRaCe (FKG, La Chaux-de-Fonds, Switzerland) has been introduced (Fig. 2.2a). BioRaCe instruments possess the same physical characteristics of RaCe instruments with alternating

cutting edges to avoid self-threading, non-cutting safety tips, sharp cutting edges with triangular sections, and both instruments have electro-chemically polished surfaces. BioRaCe differs from standard RaCe in regard to instrument taper, size and sequence. Manufacturers claim that the design of BioRaCe allows achieving sufficient apical preparation sizes with fewer number of instruments (Debelian & Trope 2008).

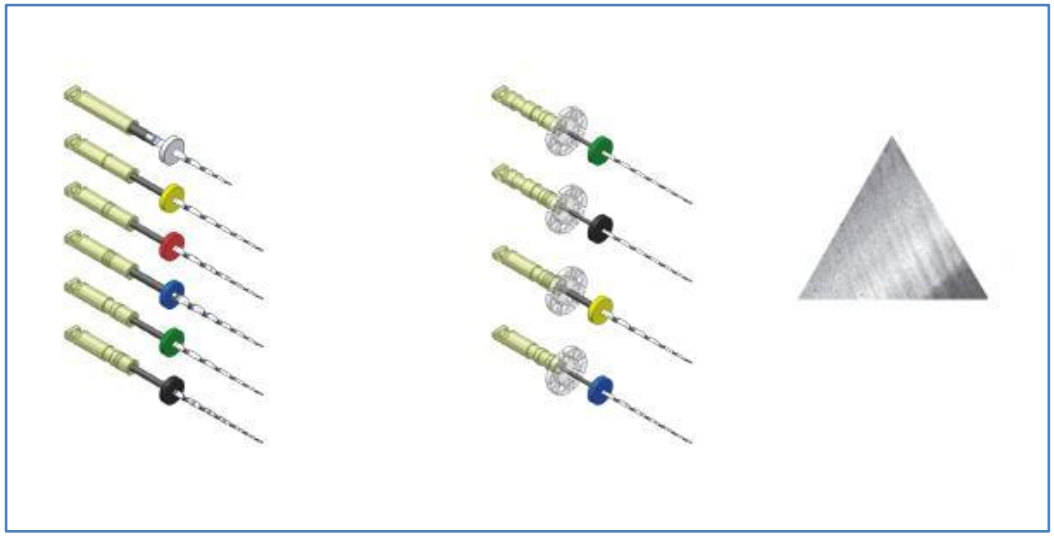


Figure 2.2a BioRaCe instruments; left: basic kit, middle: extended kit, right: triangular cross-section. (Modified from http://www.biorace.ch).

BioRaCe has two sets of instruments, basic and extended. The basic set contains six instruments (BR0-25/0.08, BR1-15/0.05, BR2-25/0.04, BR3-25/0.06, BR4-35/0.04 and BR5-40/0.04) and is recommended for use in the majority of root canal anatomies. The extended set consists of instruments for canals with severe curvature (BR4C-35/0.02 and BR5C-40/0.02) and instruments for extra widening (BR6-50/0.04 and BR7-60/0.02). Because of its low torque requirements, BioRaCe can be used between 500 to 600 rpm. The unique aspect of the BioRaCe sequence is that the areas of contact of each file are such as to minimize stress on the files so that they can be safely used at

full working length. With the exception of BR0, all BioRaCe instruments should be taken to full working length. There have been few studies published on the BioRaCe instruments. Bonaccorso *et al.* (2009) compared the shaping ability of ProTaper (Dentsply Maillefer), Mtwo (Sweden & Martina), BioRaCe (FKG) and BioRaCe + S-Apex (FKG) and concluded that less tapered and more flexible instruments like S-Apex are superior when preparing S-shaped canals. Lopes *et al.* (2010) found that the electropolishing surface treatment of BioRaCe instruments significantly increased the cyclic fatigue resistance. Siqueira *et al.* (2010) found that BioRaCe instruments were less effective than the self-adjusting file (ReDent-Nova, Ra'anana, Israel) in disinfecting long oval root canals *in vitro*.

AlphaKite instruments

In 2005, a newly developed rotary NiTi system was introduced to the market; the Alpha System (Komet, Lemgo, Germany) (Vaudt *et al.* 2009). The Alpha System consists of three different instrument sequences according to root canal size (small, average and large canals). The basic set consists of five instruments with tapers ranging from 0.10 to 0.02, and sizes ranging from 20 to 35. The surface of these files is refined by a special titanium nitride coating. The manufacturer claims that this special surface coating prevents premature blunting of the blades. The instruments have a non-cutting safety tip and a five-edged (pentagon) cross-section. For coronal flaring, an instrument with a 0.10 taper is available with a kite-shaped cross-section. The instruments are typically used in the crown-down technique with a motor speed of 250 rpm except for the 0.10 tapered instruments (500 rpm). There have been very few studies published on this system (Schäfer & Oitzinger 2008, Vaudt *et al.* 2009). A new system was introduced by the same company, AlphaKite (Komet, Lemgo, Germany) which differs from the Alpha System in that all of the instruments have a kite-shaped cross-section, with one cutting angle and 3 supporting cutting angles. The files contained in the system can be combined in many different ways to suit the

operator's requirements. To the best of our knowledge, there have been no studies published on the AlphaKite instruments.

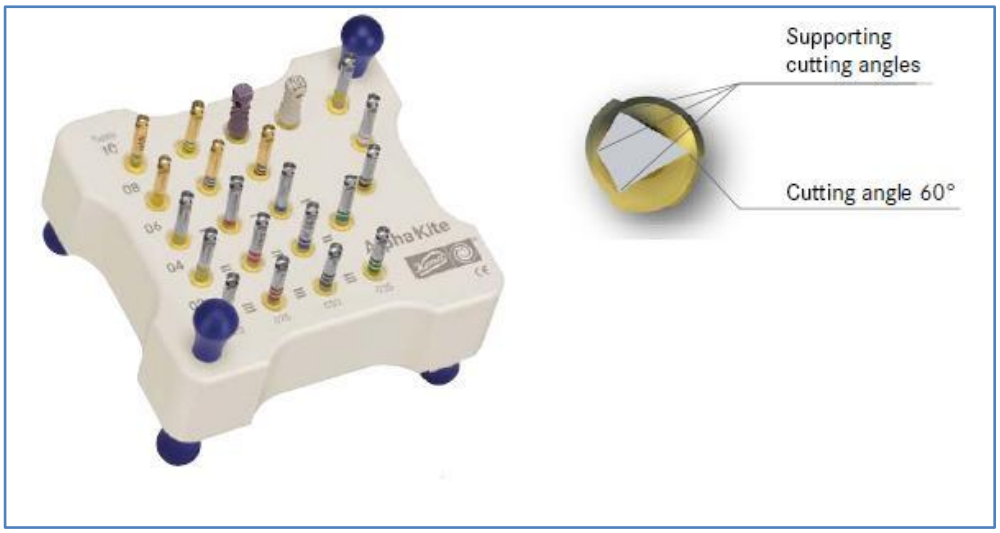


Figure 2.2b AlphaKite instruments; right: kite-shape cross-section. (Modified from http://www.brasseler.de).

2.3 Micro-computed tomography

Micro-computed tomography, similar to computed tomography (CT), uses x-rays to create cross-sections of a three-dimensional (3-D) object that are used to recreate a 3-D virtual model without destroying the original model. The pixel sizes of the cross-sections are in the micrometer range, hence the terms micro-computed tomography, micro-CT (μCT), micro-computer tomography, and high resolution x-ray tomography.

Early studies using traditional computed tomography technology for small objects were compromised by limited vertical resolution capacity of 1-2 mm. The low resolution was inadequate for reconstruction of small objects such as teeth or root canals (Nielsen *et al.* 1995). The development of the micro-CT system in the early 1980s (Elliott & Dover 1982) increased the vertical resolution capacity to 100-200 μm

(Nielsen *et al.* 1995, Bjorndal *et al.* 1999). It is much smaller than the conventional medical CT system and is used to model smaller objects. Unlike the medical CT system, in the micro-CT system the x-ray source is stationary while the specimen rotates around a single axis of rotation with a fixed rotation step (Davis & Wong 1996). X-ray transmission images are taken at each angular position and cross-sectional images of the object are reconstructed using a reconstruction algorithm (Feldkamp *et al.* 1984) to create a complete 3-D representation of the object.

In recent years resolution of micro-CT was further improved to 81 μm (Rhodes *et al.* 1999) or to resolution values < 40 μm (Dowker *et al.* 1997, Peters *et al.* 2000). At present, axial scanning steps of < 10 μm are achievable. There are various types of x-ray micro-tomography systems available; these include synchrotron based systems which produce parallel monochromatic x-rays and commercial and in-house developed desktop systems which produce cone beam polychromatic x-rays (Huang *et al.* 2007). Systems that utilize polychromatic x-rays exhibit beam hardening (BH), where x-rays of lower energy are attenuated at the outer part of the scanned object creating a false impression of higher density at the surface and lower density in the central area (Postnov *et al.* 2003). BH is the most common artifact in CT scanning. Metal filters can be installed in the path of the beam to cut away the low-energy x-rays to enhance the quality of the radiation and to minimize artifacts that can distort the image.

Micro-CT is non-destructive and non-invasive and offers significant advances in the ability to reconstruct 3-D images of tissues of the tooth before, during, and after *in vitro* treatment with optimum details. All of the extremely detailed data on each tooth before and after *in vitro* remain fully retrievable for future evaluations. Micro-CT offers several advantages compared to other evaluation methods such as sectioning or decalcification. The latter are time-consuming, complicated, and may encounter artifacts and distortion of the internal anatomy of the tooth. Evaluation using sectioning requires destruction of the tooth, and therefore loss of data can

occur. In micro-CT, reconstructed images may be rotated in any plane and two-dimensional slices can be created along any 3-D axis and can be viewed without being affected by overlapping attenuation from superimposed structures as with conventional radiographic imaging.

Micro-computed tomography and research

Micro-CT has been used as a research tool in many different applications. This technique was used to evaluate bone structure (Müller *et al.* 1998), enamel thickness (Spoor *et al.* 1993) and the mineral density of enamel white spot lesions (Huang *et al.* 2007).

Nielsen *et al.* (1995) explored the usefulness of micro-CT for endodontic investigation, and demonstrated the ability of this technique to present accurately the external and internal morphologies of the tooth without tooth destruction; the possibility of showing changes over time in surface areas and volumes of tissues; the ability to assess area and volume changes after instrumentation or obturation; and the capability of evaluating canal transportation. Dowker *et al.* (1997) reported that computed tomography imaging of teeth at the resolution of micro-CT could never be used as a clinical technique because of the very high radiation dose that would be received by the patient. However, the authors described micro-CT imaging as a powerful *in vitro* method, with applications in endodontics teaching and research. Rhodes *et al.* (1999) concluded that micro-CT is accurate for experimental endodontology. Peters *et al.* (2000) confirmed the potential and accuracy of micro-CT for detailing root canal geometry and developed a method for accurate 3-D reconstruction of root canal systems.

Micro-CT was used in the 3-D analysis of pulp chambers in maxillary second deciduous molars (Amano *et al.* 2006) and in the analysis of the morphology of molars with complex root canals (Guillaume *et al.* 2006, Plotino *et al.* 2006), premolars with long oval canals (Grande *et al.* 2008), C-shaped canals (Fan *et al.* 2004a, 2004b),

and canal isthmuses (Mannocci *et al.* 2005, Gu *et al.* 2009) and to analyze the root canal curvature in maxillary first molars (Lee *et al.* 2006). Micro-CT have also been used to scan filled roots and three-dimensionally reconstruct them to measure the adaptation of the root filling to the canal walls (Jung *et al.* 2005b, Hammad *et al.* 2009). Qualitative and quantitative correlation between histological and micro-CT examination of root canal fillings was high (Jung *et al.* 2005b). Other studies used micro-CT to analyze the cutting behavior of NiTi rotary instruments (Shen & Haapasalo 2008), to assess coronal leakage of intra-orifice barriers (Zakizadeh *et al.* 2008) and to assess changes of root canal space after the removal of fractured files (Madarati *et al.* 2009).

Several studies used micro-CT to evaluate changes in root canal shape after instrumentation (Hübscher *et al.* 2003, Peters *et al.* 2003a, Paqué *et al.* 2005a), instrumentation of C-shaped canals (Cheung & Cheung 2008), to compare the shaping of root canals by different instrumentation techniques (Rhodes *et al.* 2000, Gluskin *et al.* 2001, Peters *et al.* 2001b, Peru *et al.* 2006, Gekelman *et al.* 2009) and to evaluate the effectiveness of hand and rotary instrumentation for retreatment of canals filled with different obturation materials (Hammad *et al.* 2008). Thus, micro-CT has proved to be a viable accurate method for endodontic research.

During the scanning process, the object is mounted to the precision base which rotates over 180 or 360 degrees with a fixed rotation step. Transmission images of the sample are then taken at each rotation step. A set of data is created for the scanned sample. The size of the data depends on the total rotation chosen (180 or 360 degrees) and the rotation step selected (width of rotation angle). The degree of rotation and the rotation step selected have an effect on the scanning duration. Newer micro-CT systems have shorter scanning times than previous systems. For example, in SkyScan 1172 (SkyScan N.V., Aartselaar, Belgium) the x-ray source and the camera are closer together than in previous versions, thus increasing the intensity of the x-rays on the

camera, and therefore reducing the scanning time. The micro-CT system used in this study and parameters of scanning and reconstruction are detailed in Chapter 3.

2.4 Aim of the study

The aim of this study was to evaluate, using micro-computed tomography, the root canal transportation and centering ability of BioRaCe and AlphaKite rotary instruments, and their ability to eradicate canal variations after preparation of the mesiobuccal root of the maxillary first molar tooth.

2.5 Hypotheses

1) Due to the interaction of nickel-titanium properties, instrument design, and preparation technique, the shaping outcomes with new rotary NiTi files are mostly predictable. Both BioRaCe and AlphaKite instruments will produce well centered and tapered preparations with minimal canal transportation.
2) Canal variations of the mesiobuccal root of the maxillary first molar will not be eradicated because of the complex anatomy of the mesiobuccal root.

CHAPTER 3: MATERIALS AND METHODS

3.1 Preparation of specimens

A total of 20 maxillary first molar teeth with fully formed apices that were extracted for periodontal and prosthetic reasons were selected for the study, ethical approval University of Otago (10/033). Tissue fragments and calcified debris were removed by scaling and the teeth were stored in 10% formalin until used. Prior to the study the teeth were washed with distilled water to rinse off the formalin.

The specimens were first categorized according to the degree of canal curvature of the mesiobuccal root. To determine the canal's curvature, the teeth were radiographed using an X-ray machine (Intra Prostyle, Planmeca Oy, Helsinki, Finland) operated at 8 mA, 60 kVp, in both a bucco-lingual plane and a mesio-distal plane. The focus-film-distance was 35 cm. A digital radiographic system (Digora® Optime, Soredex, Finland) that uses a memory phosphor plate in place of the film, was used to receive and scan the image. Each image was enlarged to fit a size A4 sheet and then printed on white paper. Curvatures were judged according to the criteria described by Schneider (1971). The radius of curvature was not considered because it is most significant when determining fatigue resistance of rotary NiTi files (Haïkel *et al.* 1999) which is not the scope of this study.

Briefly, a line was drawn on the reproduced image parallel to the long axis of the canal. A second line was drawn from the apical foramen to intersect with the first line at the point where the canal leaves the long axis of the tooth (Fig. 3.1a). Using a protractor, the acute angle that formed was measured and the specimens were classified as follows: straight curvature when the angle measured was 5 degrees or less; moderate curvature when the angle measured was 10-20 degrees; and severe curvature when the angle measured was from 25-70 degrees. The specimens were

then divided into two groups of ten ensuring an even distribution of canal curvatures across the two groups.

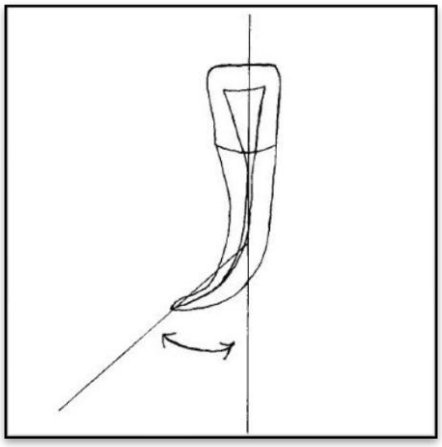


Figure 3.1a Example of how the degree of root curvature was determined (from Schneider 1971).

The mesiobuccal root of each tooth was resected at the furcation level using a water-cooled rotary diamond saw (Gillings-Hamco, Rochester, NY, USA). The length of the roots measured approximately 10 mm. Custom-made moulds with an internal diameter of 20 mm that fitted exactly onto the scanning platform were constructed to ensure subsequent precise repositioning of the specimens onto the scanning system (Fig. 3.1b (i, ii)). The mesiobuccal root was mounted onto the scanning platform using modelling paste (Plastilina, Jovi S.A., Spain) (Fig. 3.1b (iii)). Acrylic (Castapress, Vertex-Dental B.V., the Netherlands) was carefully poured into the moulds, ensuring that the coronal part of the root remained exposed (Fig. 3.1b (iv)). The moulds were placed on a side until the acrylic was fully set. The specimens were then removed from the moulds, and the modelling paste was removed to expose the apical tip of the root (Fig. 3.1b (v, vi)). An adhesive radiopaque grid (X-ray mesh, Hager & Werken GmbH & Co. KG, Germany) was attached to the acrylic to be used as a reference guide when comparing the pre- and post-instrumentation scans (Fig. 3.1b (vii)).

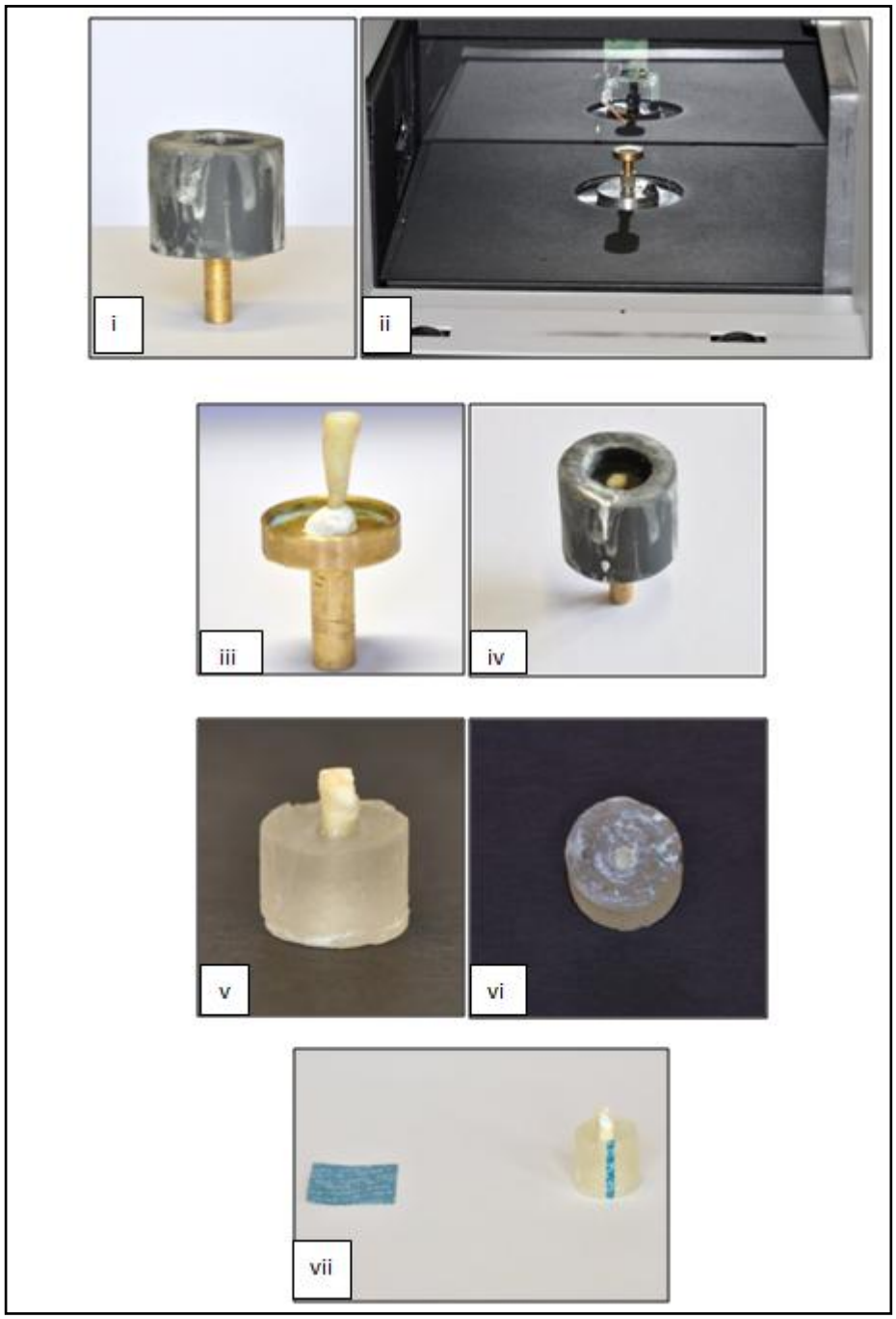


Figure 3.1b Preparation of specimens: **i)** Custom-made mould fitted onto the scanning platform; **ii)** Micro-CT chamber showing scanning platform; **iii)** Mesiobuccal root mounted onto the scanning platform using modeling paste; **iv)** Acrylic poured ensuring coronal part of the root remained exposed; **v)** Mesiobuccal root embedded in acrylic; **vi)** Mesiobuccal root apical tip visible after removing modeling paste; **vii)** Adhesive x-ray grid (left) attached on specimen (right).

3.2 Root canal preparation

The two groups were assigned for preparation by either BioRaCe (FKG Dentaire, Switzerland), or AlphaKite instruments (Komet, Germany). The canals were prepared by the primary researcher (A. A.). The specimens were hand-held during the preparation to allow easy access and a surgical microscope (Carl Zeiss, Germany) was used to help locate a second mesiobuccal (MB2) canal. After establishing straight line access to a canal, the working length (WL) was determined using an ISO 10 stainless steel K-file (Dentsply Maillefer, Ballaigues, Switzerland) placed 1 mm short of the length when the file tip was just visible at the apical formina. The canal was irrigated between each file using 2.5% NaOCl (School of Pharmacy, University of Otago). A light coating of Glyde™ File Prep (Dentsply Maillefer, Ballaigues, Switzerland) was applied to a file as a lubricant and an apical glide path using ISO 15 stainless steel K-files (Dentsply Maillefer) was established. Each rotary system was used according to manufacturers' guidelines. An ISO 15 stainless steel K-file was used during the preparation to recapitulate to full WL before moving to the next file in sequence. All instruments were rotated in a 16:1 speed-reducing handpiece powered by a high torque electric motor (Tecknica/ATR motor, Pistoia, Italy) and the flutes were cleaned of debris after each insertion. Each file was used to prepare five mesiobuccal roots and was then discarded.

The following rotary sequence was used with BioRaCe instruments according to manufacturer's recommendations:

1. BR0 (25/0.08) with 4 gentle strokes. The preparation was repeated until approximately 4-6 mm of the coronal part of the canal was prepared.
2. BR1 (15/0.05) with 4 gentle strokes to the WL. If this instrument did not reach the WL, the instrument was removed, cleaned and reinserted into the canal until the WL was achieved.
3. BR2 (25/0.04) and BR3 (25/0.06) as described for BR1.

4. BR4 (35/0.04) for final apical preparation using the same principle as described for BR1-3.

The BioRaCe instruments were run at a speed of 500 rpm with a torque value of 1 Ncm.

The AlphaKite system was used according to manufacturer's recommendations in a crown-down technique:

1. AK (30/0.08) for the coronal third of the canal. Motor speed 250 rpm, torque 1.2 Ncm.
2. AK (25/0.06) for the coronal third of the canal and the initial part of the curve. Motor speed 250 rpm, torque 0.7 Ncm.
3. AK (25/0.04) for the middle part and transcending the curve of the canal. Motor speed 250 rpm, torque 0.4 Ncm.
4. AK (25/0.02) for the apical region, motor speed 250 rpm and torque 0.3 Ncm. The preparation was enlarged by two sizes to AK (35/0.02), using the same motor speed, but with torque values of 0.4 Ncm for size 30 and 0.7 Ncm for size 35. The apical preparation was enlarged to size 35 to be similar to the final apical size in BioRaCe instruments.

3.3 Micro-CT scanning

A SkyScan 1172 scanner (SkyScan N.V., Aartselaar, Belgium), capable of reaching a spatial resolution of 5 μm corresponding to near 1 x 10^{-7} cubic mm voxel size was used in this study (Fig. 3.3a). The system consists of high voltage x-ray microfocus tube with 8 μm focal spot operating at 20-80 kV and 100 μA and a precision object manipulator for moving the sample in translational movement in two dimensions as well as rotational movement. The system has a twelve-bit digital cooled charged coupled device (CCD) camera based on 4000 x 2300 (10 Mp), or 1280 x 1024 (1.3 Mp)

cooled CCD sensor with fibre-optic coupling to the x-ray scintillator. The specifications of the scanning parameters used are outlined in Table 3.3a.

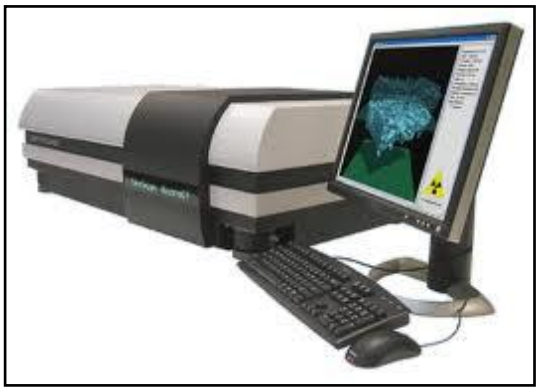


Figure 3.3a SkyScan 1172 (from http://www.skyscan.be).

The specimens were scanned pre-instrumentation without probing the canals for patency to avoid modifying their anatomy (Fig. 3.3b). The acrylic specimens and the scanning platform, together with the scanner itself, were all marked to ensure exact repositioning of the samples pre- and post-instrumentation.

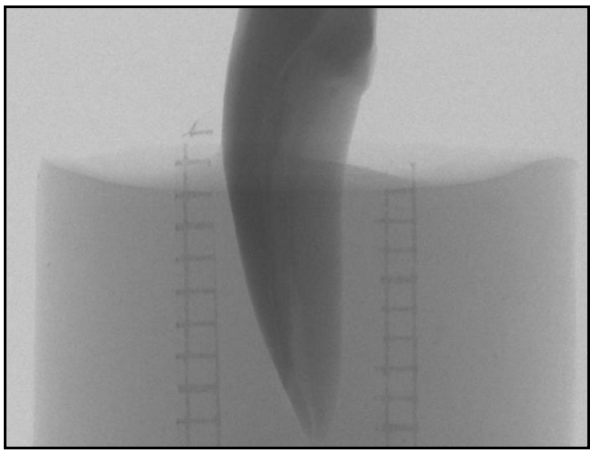


Figure 3.3b Example of an image created for a MB root after scanning.

Table 3.3a Scanning parameters used in the study

Parameter	Specification
Camera	Hamamatsu 10Mp
Camera Pixel Size (µm)	11.57
Camera to Source (mm)	282.399
Depth (bits)	16
Exposure (ms)	1475
Filter	Al+Cu
Flat Field Correction	ON
Frame Averaging	ON (4)
Geometrical Correction	ON
Image Format	TIFF
Image Pixel Size (µm)	15.96- 17.35
Median Filtering	ON
Number of Columns	2000
Number of Rows	1048
Object to Source (mm)	194.780
Random Movement	ON (20)
Rotation Step (deg)	0.4
Scan duration (approximately)	1 hour
Software	SkyScan 1172 Version 1. 5
Source Current (µA)	100
Source Voltage (kV)	100
Use 360 Rotation	NO
Geometrical Correction	Activated
Median filtering	Activated
Flat Field Correction	Activated
Scan duration (approximately)	50 minutes

The MB roots were scanned again after canal preparation. Cross-sectional slices of the pre- and post-scans were then reconstructed from the set of the acquired angular projections using a modified Feldkamp cone beam algorithm (NRecon, Version 1.5.1.4) (Fig. 3.3c). The reconstructed cross-sectional slices have a 1000 x 1000 to 800 x 8000 pixels format, with an isotropic pixels size between 0.9-35 μm. The cross-sectional images produced can be saved in BMP, TIFF, JPEG or numerical data format. Special mathematical corrections through the reconstruction process can be used to overcome artifacts created during the scanning. The parameters used for the reconstruction are detailed in Table 3.3b. On average, 950 slices were created for each MB root.

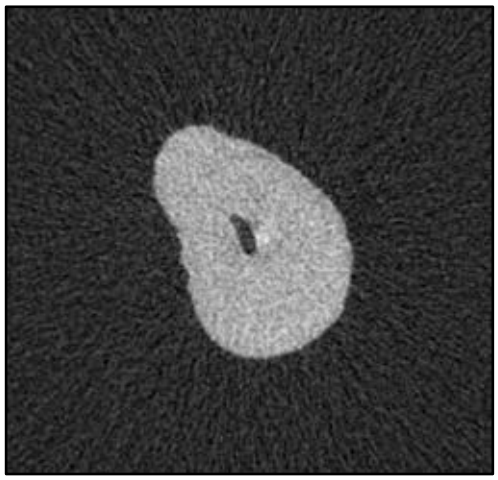


Figure 3.3c Example of a cross-sectional image created for a specimen.

Table 3.3b Reconstruction parameters used in the study

Parameter	Specification
Result File Type	TIFF
Result File Header Length (bytes)	12
Result Image Width (pixels)	2000
Result Image Height (pixels)	2000
Average Pixel Size (μm)	17.01259
Ring Artifact Correction	20
Beam Hardening Correction (%)	70-80

Three-dimensional (3-D) reconstruction

Three-dimensional images of the roots were reconstructed using appropriate processing software package. Data from the cross-sectional images were downsized using a file-converting program T Converter (ECAD-2-12210 PMC; Mercury Computer System Inc., Chelmsford, MA, USA) for convenient use. The registered images were then processed using 3-D visualization software (Amira 4.1; Visage Imaging Inc., USA), to create 3-D images of the roots and the canals for the qualitative assessment (Figs. 3.3d, e).

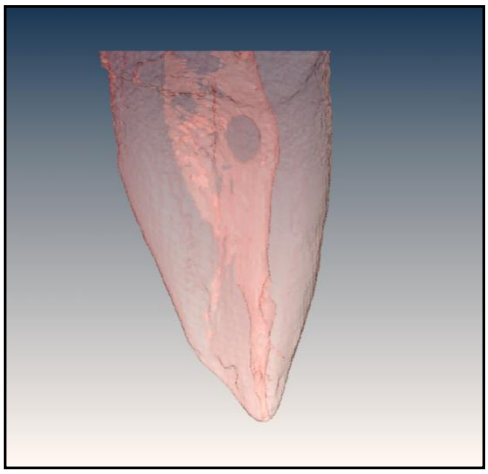


Figure 3.3d Example of an image created by Amira software (mesio-distal plane).

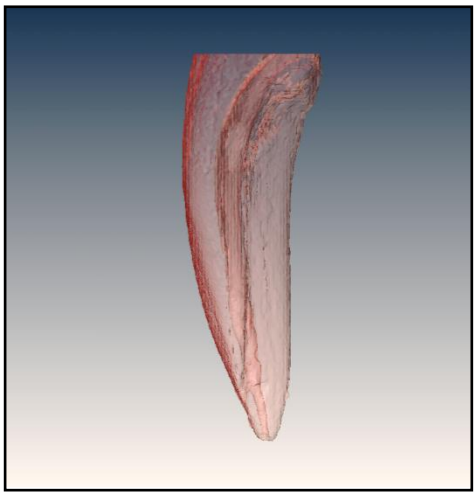


Figure 3.3e Example of an image created by Amira software (bucco-lingual plane).

3.4 Image analysis

Quantitative image analysis

Software package CT Analyser (Version 1.5.0.0, Sky Scan N.V., Aartselaar, Belgium) was used for the quantitative assessment of the images. The metal grid was used as a reference radio-opaque point for standardizing the pre- and post-instrumentation cross-sections of the roots. Using the grid as a guide, the point that was 11.0 mm

above the apical tip was determined, and from this point downwards, ten slices were chosen. Each cross-sectional slice was 1.0 mm apical to the previous slice. The last slice measured 1.0 mm (STD= 0.35) from the apical tip of the root. Cross-sectional slices of the teeth at the ten levels were used to evaluate transportation and centering ratio at the first mesiobuccal canal only as the second mesiobuccal canal was not present in all specimens. Data were arranged into three groups; coronal (levels 10, 9, 8), middle (levels 7, 6, 5, 4), and apical (levels 3, 2, and 1).

To compare the degree of canal transportation, a technique developed by Gambill *et al.* (1996) was used. The amount of transportation was determined by measuring the shortest distance from the edge of the uninstrumented canal to the periphery of the root, in both a mesial and distal direction, and then comparing this with the same measurements obtained from the instrumented images (Fig. 3.4a).

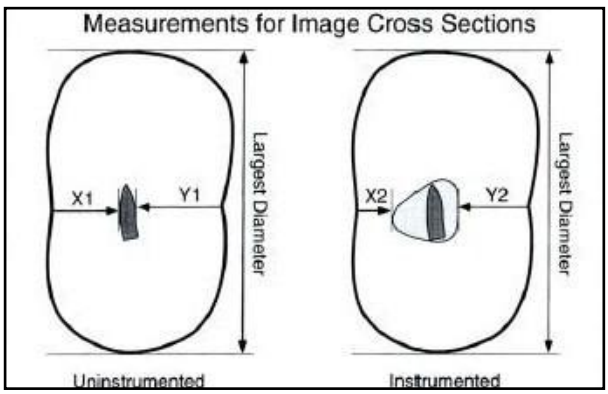


Figure 3.4a Diagram representing how X1, X2, Y1 & Y2 were derived (from Gambill *et al.* 1996).

The following formula was used for the calculation of transportation: [(X1-X2)-(Y1-Y2)], where X1 represents the shortest distance from the outside of the curved root to the periphery of the uninstrumented canal, Y1 represents the shortest distance from the inside (furcation) of the curved root to the periphery of the uninstrumented canal, X2 represents the shortest distance from the outside of the curved root to the

periphery of the instrumented canal, and Y2 represents the shortest distance from the inside of the curved root to the periphery of the instrumented canal.

According to this formula, a result of '0' indicates no canal transportation. A result other than '0' means that transportation has occurred in the canal; a negative result indicates transportation toward the inside of the curve and a positive result indicates transportation toward the outside of the curve.

According to Gambill *et al.* (1996), the mean centering ratio indicates the ability of the instrument to stay centered in the canal. This ratio was calculated for both BioRaCe and AlphaKite rotary systems at each of the ten levels using the following formula:

[(X1-X2)/ (Y1-Y2)] or [(Y1-Y2)/(X1-X2)]

The formula was chosen according to the numbered value that should always be the lowest of the results obtained through the difference. According to this formula, a result of '1' indicates perfect centering. The closer the result is to zero, the worse the ability of the instrument to keep itself in the central axis of the canal. To better describe the centering ability this study further quantified the centering ratio as: 1 = perfect centering ability, (0.6 – < 1) = good centering ability, (0.4 – < 0.6) = moderate centering ability, (> 0 – < 0.4) = poor centering ability, 0 = not centered.

The values of X1, X2, Y1 and Y2 were measured by the primary researcher (A. A.). The measurements were repeated again after one week, and transportation was recalculated to examine the intra-examiner reliability.

Statistical analysis

Mean scores were calculated for the 3 coronal, 4 middle and 3 apical measurements for each root, using Microsoft Office Excel software package. The transportation and centering ratio results were analyzed statistically using SPSS for windows (IBM® SPSS® Statistics 19, NY). Transportation and centering ratio results were compared

between the two systems and within each system at the coronal, middle and apical levels. Preliminary tests were conducted to verify the normality of the data distribution. Initial tests indicated that the data were normally distributed. Subsequently, parametric statistical tests (*t*-test and ANOVA) were applied to determine any statistically significant differences, together with post-hoc comparisons to verify the difference amongst the groups. A 0.05 level of confidence was used for all analyses.

The intra-examiner reliability was assessed in two different ways. The first way was by creating a Bland-Altman plot (Bland & Altman 1986,1996) using the SPSS software, by assigning the mean of the two transportation measurements as the abscissa (x-axis) value, and the difference between the two values as the ordinate (y-axis) value. Limits of agreement were computed; as bias ± 1.96 STD (average difference ± 1.96 standard deviation of the difference). An even distribution of the data across the limits of agreement indicates good agreement. The second way was by calculating the intra-class correlation coefficient (ICC) and calculating the Cronbach's Alpha value, again using the SPSS software.

Qualitative image analysis

The pre- and post-three-dimensional reconstructed images obtained from the Amira software were analyzed. The rotary systems were evaluated on their abilities to eradicate canal variations (e.g. extra canals, apical deltas, fins, webbing, inter-canal communications, or lateral and accessory canals). A scale was developed for the comparisons:

1: canal variations not removed/instrumented
2: canal variations partially removed/instrumented
3: canal variations completely removed/instrumented

CHAPTER 4: RESULTS

Canal transportation and centering ratio results were evaluated for the first mesiobuccal canal (MB1) only as a second mesiobuccal canal (MB2) was not present in all roots. Ten MB roots were instrumented with BioRaCe and 10 MB roots were instrumented with AlphaKite. In one of the AlphaKite specimens, one file separated and the specimen was discarded. Nine AlphaKite specimens were therefore evaluated.

4.1 Canal transportation

The results for canal transportation for both systems are shown in Table 4.1a. In the coronal root section seven MB1 canals instrumented with BioRaCe were transported toward the inside of the curve (furcation) and three canals were transported toward the outside of the curve. Mean transportation at this level was -0.12 ± 0.19 mm. In the group instrumented with AlphaKite, five MB1 canals were transported toward the inside of the curve and four canals were transported toward the outside of the curve. Mean transportation was -0.05 ± 0.22 mm. There was no statistical significant difference between the two systems at the coronal levels in terms of canal transportation ($P > 0.05$).

In the middle third of the root, six MB1 canals were transported toward the inside of the curve and three canals were transported toward the outside of the curve with the BioRaCe system. In one root there was no transportation in the middle third of the canal. Mean transportation was -0.01 ± 0.09 mm. In the AlphaKite system, five canals were transported toward the inside of the curve and four canals were transported toward the outside of the curve, mean transportation was -0.04 ± 0.10 mm. The difference between the two systems at the middle levels was not statistically significant ($P > 0.05$).

In the apical levels, all canals were transported toward the outside of the curve with the BioRaCe system. Mean transportation was +0.06 ± 0.05 mm. In the AlphaKite system, eight canals were transported toward the outside, and only one canal was transported toward the inside of the curve. Mean transportation was +0.03 ± 0.03 mm. No statistically significant difference was found between the two systems at the apical levels ($P > 0.05$). The results for transportation across all three levels for BioRaCe and AlphaKite are summarized in Fig. 4.1.

Table 4.1a Transportation (mm) across root levels for both systems (mean ± STD)

		Root Level		
Group	***n***	**Coronal**	**Middle**	**Apical**
BioRaCe	10	-0.12 ± 0.19	-0.01 ± 0.09	+0.06 ± 0.05
AlphaKite	9	-0.05 ± 0.22	-0.04 ± 0.10	+0.03 ± 0.03
		($P > 0.05$)	($P > 0.05$)	($P > 0.05$)

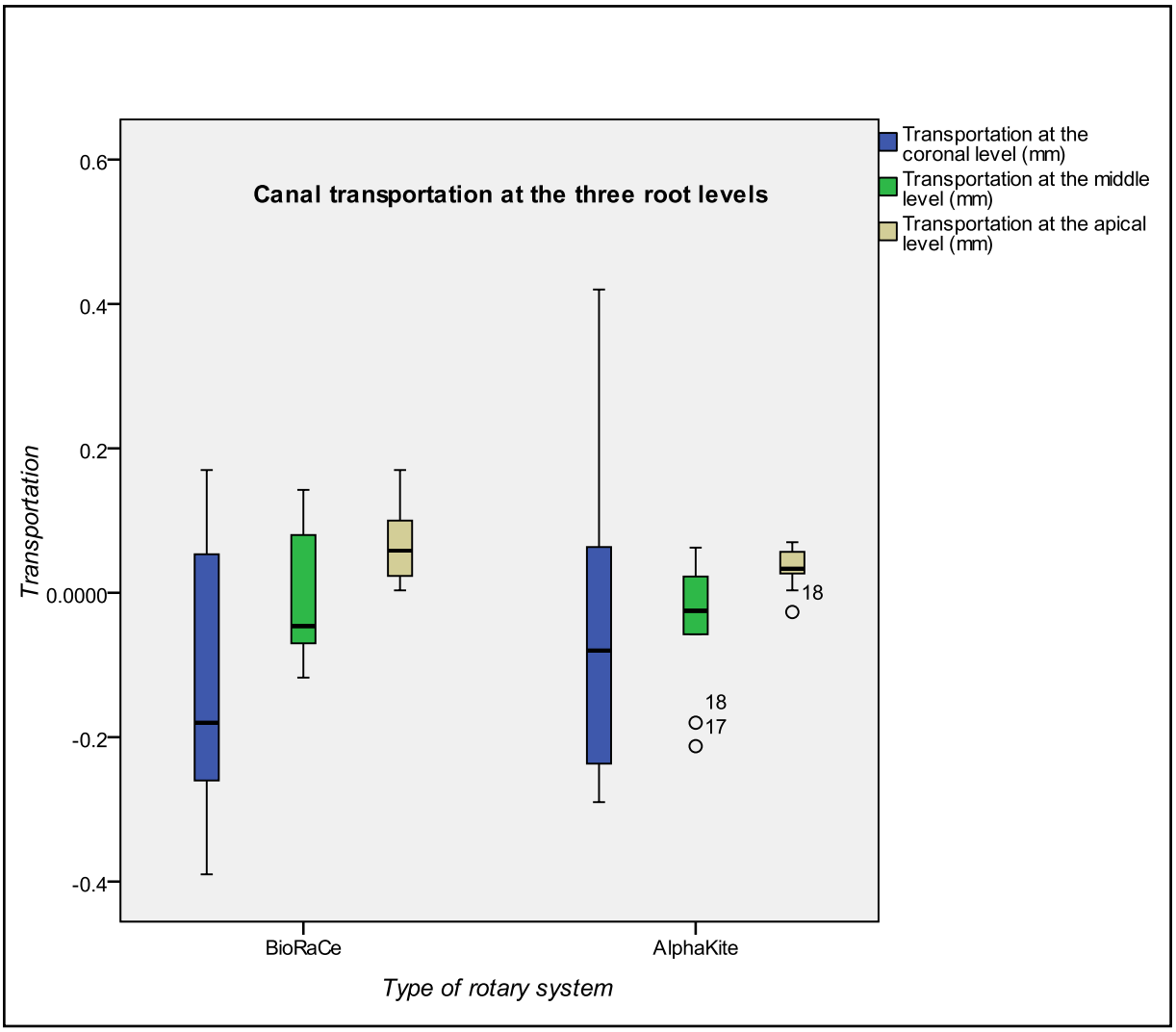


Figure 4.1 Transportation after the use of BioRaCe and AlphaKite systems showing similar values and ranges for each system at each level.

When transportation was compared across the coronal, middle and apical levels of the root for each system, a statistically significant difference was found ($P < 0.05$) in the amount of transportation in the BioRaCe system between the coronal and apical levels (Table 4.1b).

Table 4.1b Transportation (mm) across root levels for BioRaCe

	Mean (STD)	p-value
coronal	-0.12 (0.19)	0.01
middle	-0.01 (0.09)	
apical	+0.06 (0.05)	

In the AlphaKite system, no statistical significant difference was found in the amount of transportation across the three different root levels (Table 4.1c).

Table 4.1c Transportation (mm) across root levels for AlphaKite

	Mean (STD)	p-value
coronal	-0.05 (0.22)	0.40
middle	-0.04 (0.10)	
apical	+0.03 (0.03)	

4.2 Centering Ratio

The best centering ratio was at the apical levels of root canals prepared using the AlphaKite system (0.66 ± 0.24) and the worst centering ratio was at the coronal levels after preparation using the BioRaCe system (0.32 ± 0.25).

The centering ratio results for BioRaCe are shown in Table 4.2a. There were no statistically significant differences across the three root levels ($P > 0.05$).

Table 4.2a Centering Ratio across root levels for BioRaCe

	Mean (STD)	F (df)	p-value	Centering Ability
coronal	0.32 (0.25)	2.81 (2)	0.08	poor
middle	0.53 (0.23)			moderate
apical	0.57 (0.27)			moderate

Table 4.2b summarizes the centering ratio results for AlphaKite. There were no statistically significant differences across the three root levels ($P > 0.05$).

Table 4.2b Centering Ratio across root levels for AlphaKite

	Mean (STD)	F (df)	p-value	Centering Ability
coronal	0.46 (0.31)	1.07 (2)	0.36	moderate
middle	0.56 (0.29)			moderate
apical	0.66 (0.24)			good

When the centering ratio was compared between BioRaCe and AlphaKite instruments at the coronal, middle and apical levels of the root, no statistically significant differences ($P > 0.05$) were found (Table 4.2c). Nevertheless, the descriptive analysis suggests that AlphaKite produced a better centered preparation. The results for centering ratio across all three levels for BioRaCe and AlphaKite are summarized in Fig. 4.2.

Table 4.2c Centering Ratio across root levels for both systems (mean ± STD)

		Root Level		
Group	***n***	**Coronal**	**Middle**	**Apical**
BioRaCe	10	0.32 ± 0.25	0.53 ± 0.23	0.57 ± 0.27
AlphaKite	9	0.46 ± 0.31	0.56 ± 0.29	0.66 ± 0.24
		($P > 0.05$)	($P > 0.05$)	($P > 0.05$)

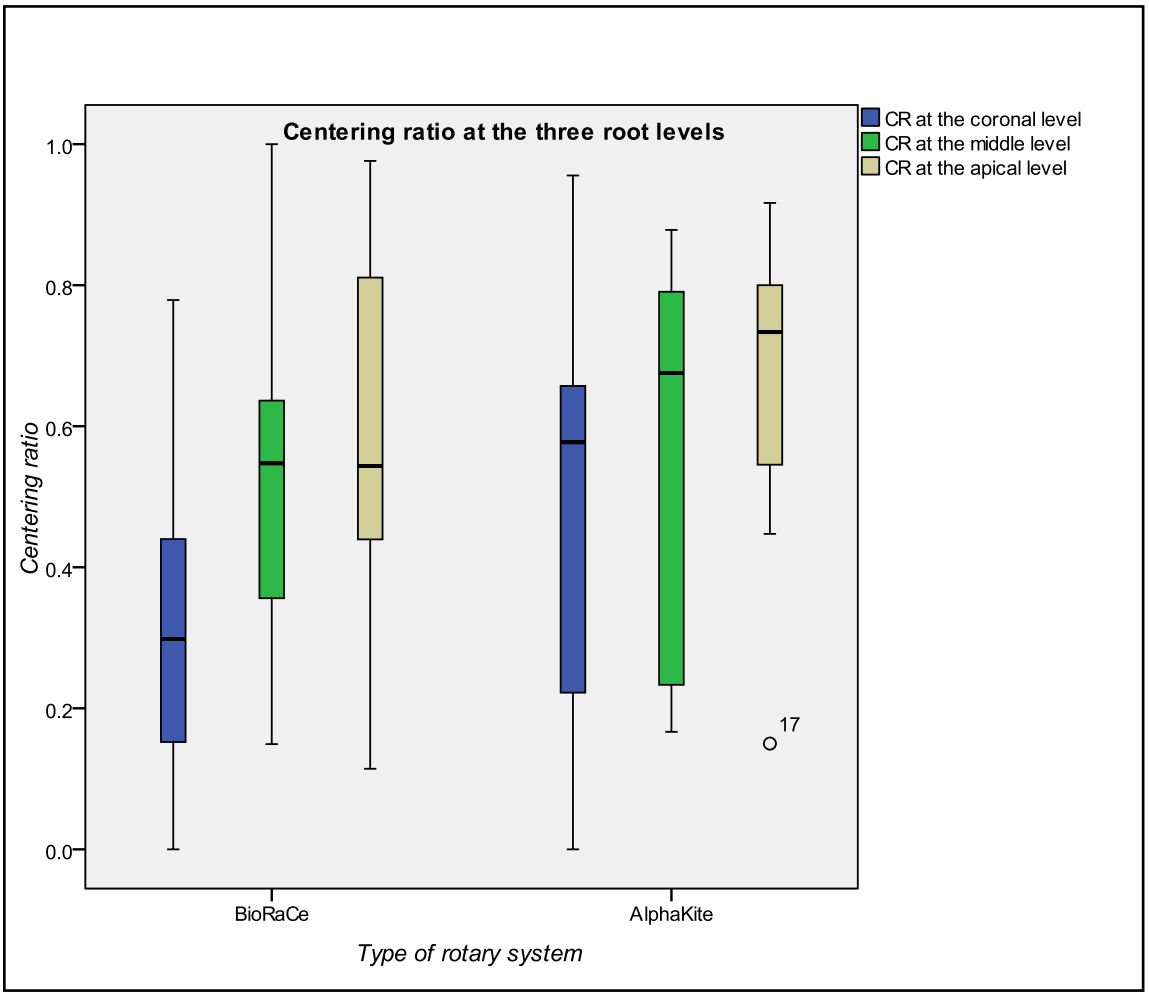


Figure 4.2 Centering Ratio (CR) for BioRaCe and AlphaKite systems showing similar values and ranges for each system at each level.

4.3 Intra-examiner reliability

A Bland-Altman plot was created for the BioRaCe system using the SPSS software. The limits of agreement for BioRaCe were 0.045 and -0.036. Most of the data lay within the limits of agreement indicating good agreement (Fig. 4.3a). High agreement was also noted when the intraclass correlation coefficient (ICC) was calculated; Chronbach's Alpha= 0.995.

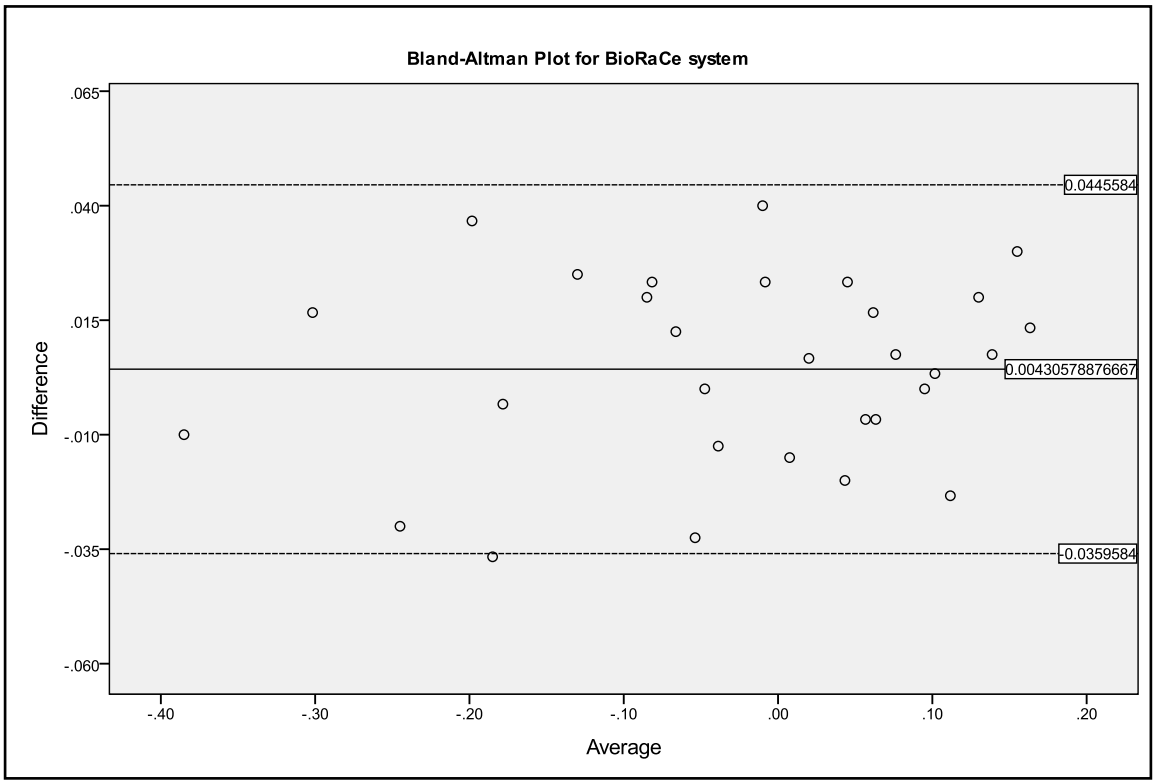


Figure 4.3a BioRaCe Bland-Altman plot (mean of difference= 0.004, STD= 0.021).

The Bland-Altman plot for the AlphaKite system is shown in Fig. 4.3b. The limits of agreement were 0.097 and -0.107. Most of the data lay within the limits of agreement indicating good agreement. High agreement was also noted when the intraclass correlation coefficient (ICC) was calculated; Chronbach's Alpha=0.965.

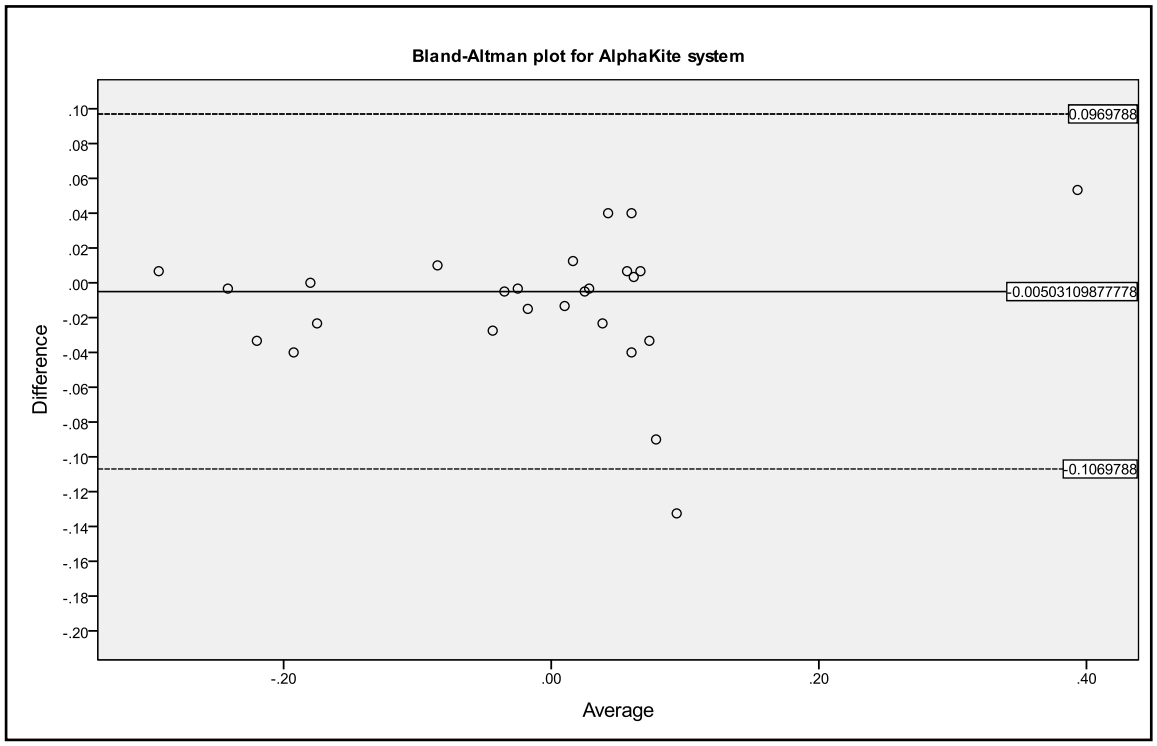


Figure 4.3b AlphaKite Bland-Altman plot (mean of difference= -0.005, STD= 0.052).

4.4 Three-dimensional image analysis

The pre- and post- three-dimensional images constructed from the Amira software were analyzed to evaluate the two systems on their abilities to eradicate canal variations.

BioRaCe

The sample consisted of 5 roots with 2 MB canals (Fig. 4.4a), and 5 roots with a single canal present in the entire length of the root (Fig. 4.4b). In the roots with two MB canals, 4 had independent MB canals (i.e. two canals with two apical foamina) and one root had two canals that joined into one canal (Fig. 4.4c). Canal variations were present in all roots. In four roots, variations were found in the coronal, middle and apical levels (Fig. 4.4d), whereas four of the roots had them in the coronal and middle

areas only (Fig. 4.4e). One root had variations in the middle areas only and one root had them in the coronal areas only (Fig. 4.4f).

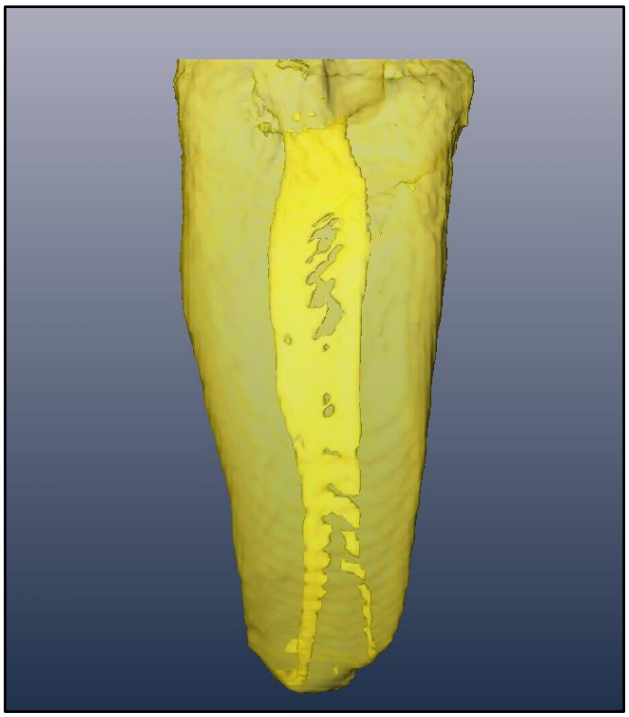


Figure 4.4a Representative root showing independent MB1 & MB2. Note inter-canal communications present in the coronal & middle areas.

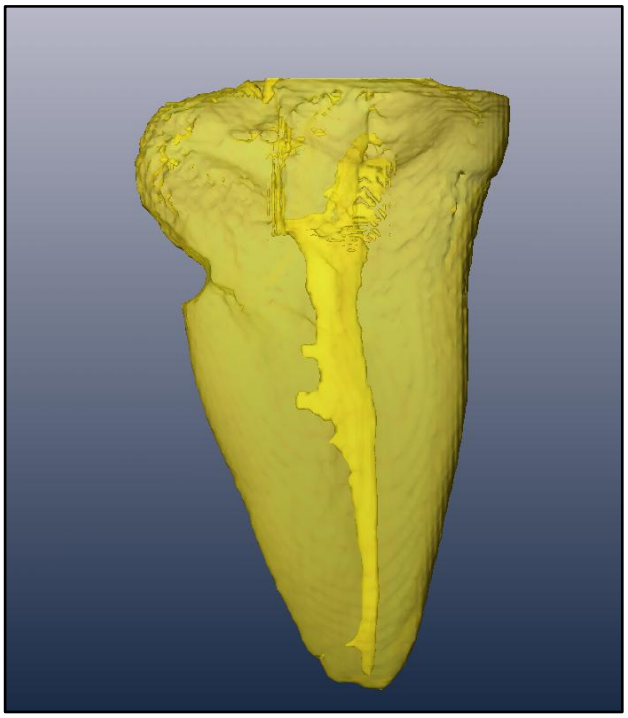


Figure 4.4b Representative root showing one canal in the entire length of the root. Note canal variations in the middle levels.

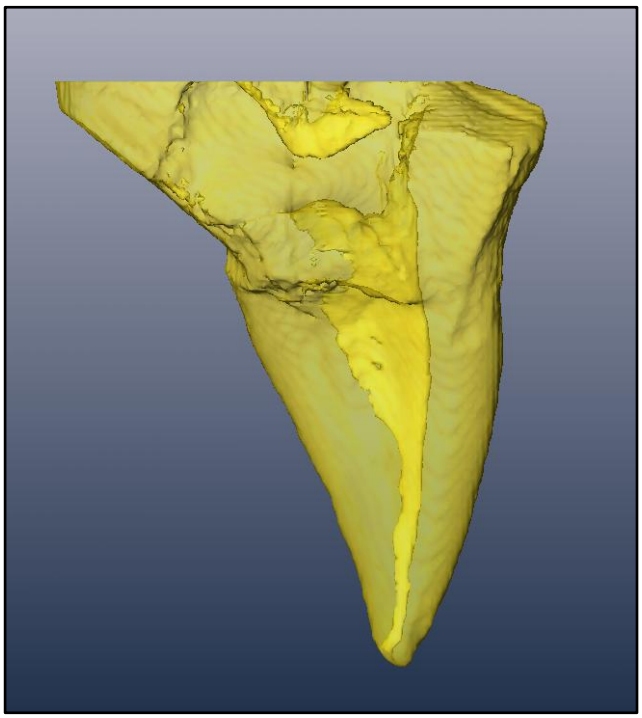


Figure 4.4c Mesiobuccal root showing two canals joining into one canal and canal variations present in the coronal & middle levels.

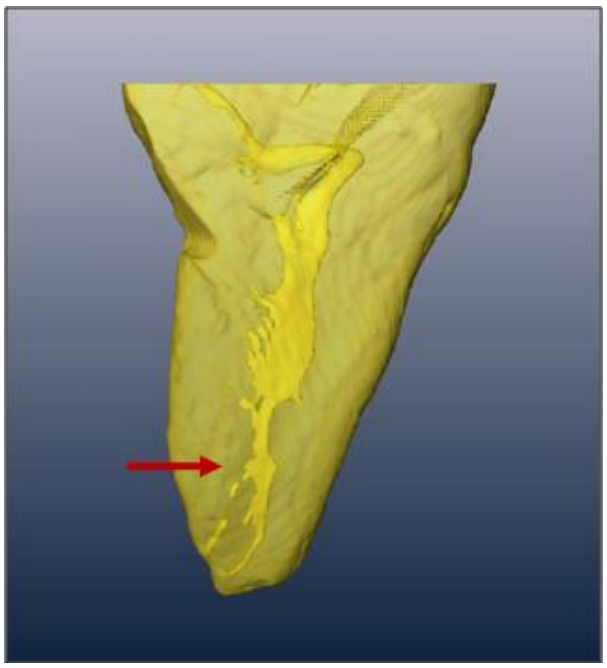


Figure 4.4d Mesiobuccal root with one canal dividing and forming an accessory canal (arrow). Note canal variations present in all levels of the root.

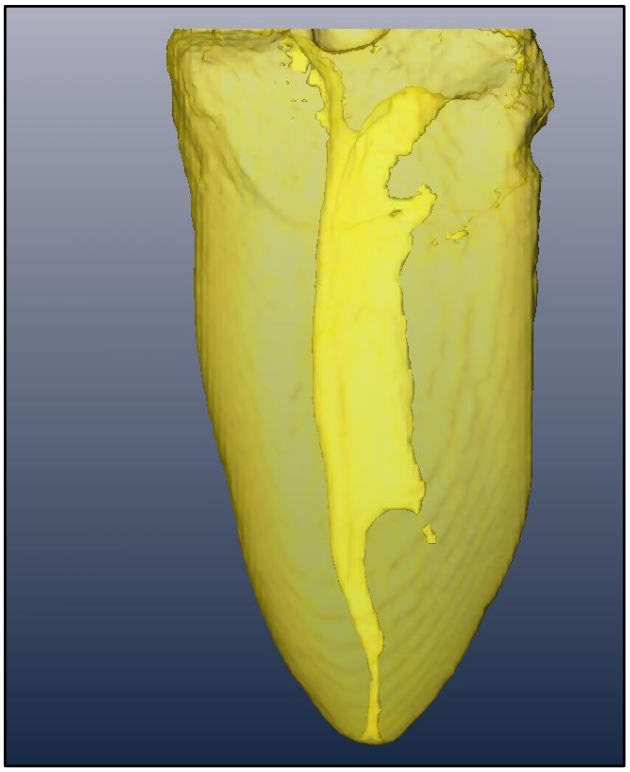


Figure 4.4e Representative mesiobuccal root showing one canal with a wide fin. Note canal variations in the coronal and middle areas.

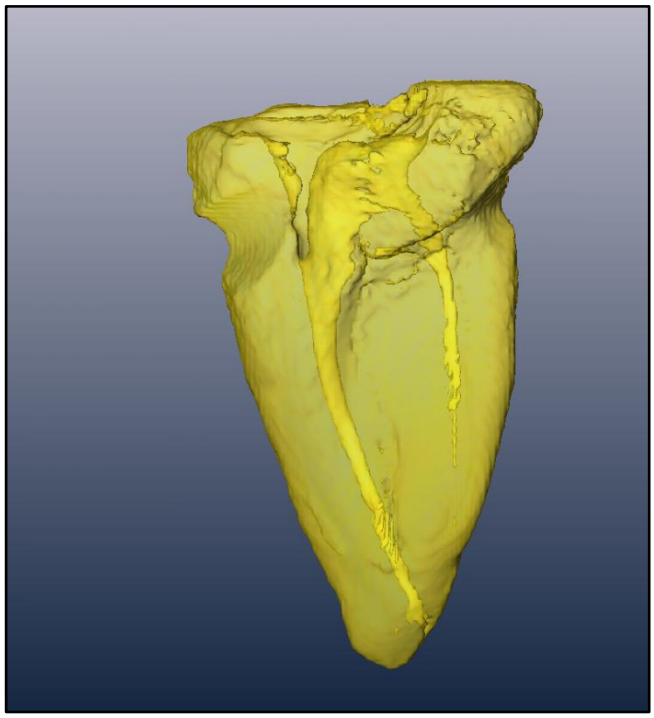


Figure 4.4f Mesiobuccal root showing canals with coronal inter-canal communication.

For the majority of the specimens, the canal variations were not removed or instrumented (6 of 10) (Fig. 4.4g). Canal variations were partially removed or instrumented in the remaining 4 roots (Fig. 4.4h). No specimens showed complete removal or instrumentation of the variations (Table 4.4).

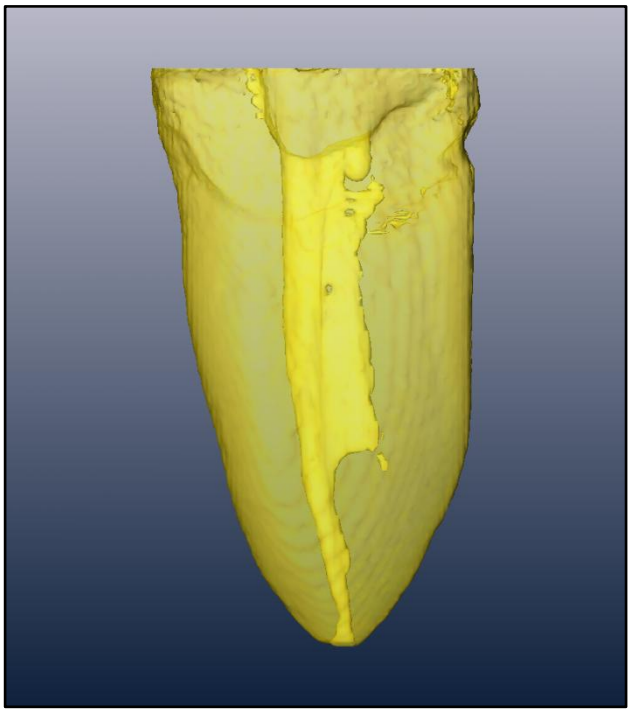


Figure 4.4g Mesiobuccal root of the canal in Figure 4.4e post-instrumentation with BioRaCe. Canal variations not removed.

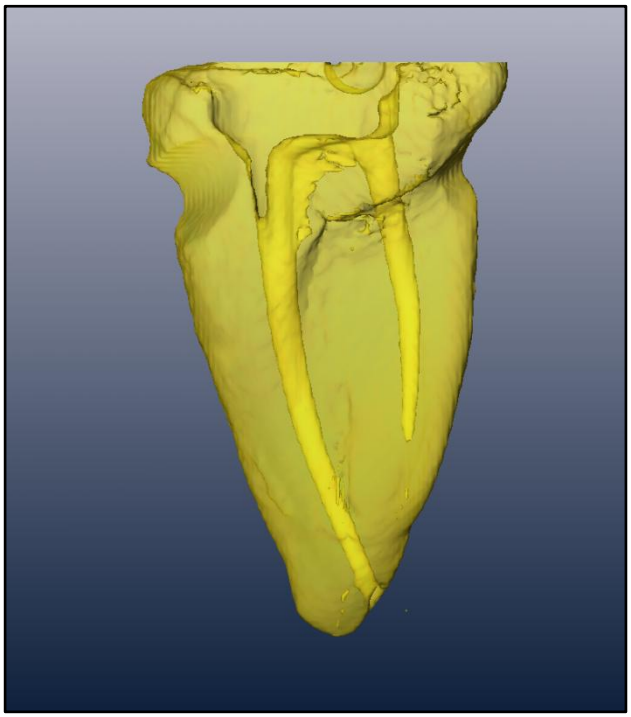


Figure 4.4h Mesiobuccal root of the canals in Figure 4.4f post-instrumentation with BioRaCe showing that the coronal inter-canal communication was partially removed.

Table 4.4 Results for removal of canal variations

Scale	BioRaCe (n=10)	AlphaKite (n=9)
1	6	8
2	4	1
3	0	0

AlphaKite

The sample consisted of 6 roots with 2 MB canals, and 3 roots with a single canal present in the entire length of the root. In the roots with two MB canals, 3 roots had independent MB canals, two roots had two canals that joined into one canal (Figs. 4.4i, j) and one root had two canals that joined in the middle level and then divided into two apically (Fig. 4.4k). Canal variations were present in all roots. In three of the roots, variations were found in the coronal, middle and apical levels (Fig. 4.4l). Four roots had variations in the coronal and middle areas only. One root had variations in the coronal and apical areas and one root had them in the coronal areas only.

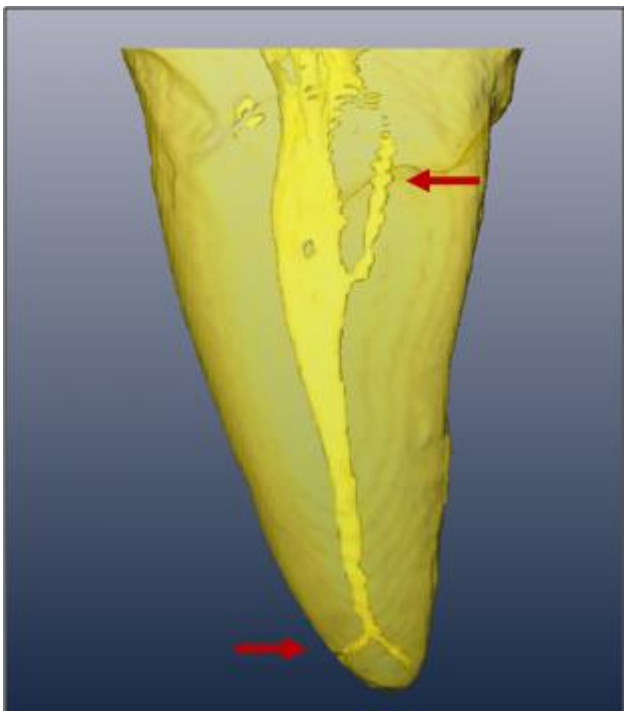


Figure 4.4i Representative mesiobuccal root showing two canals joining into one canal (top arrow pointing at MB2). Note accessory canal (bottom arrow).

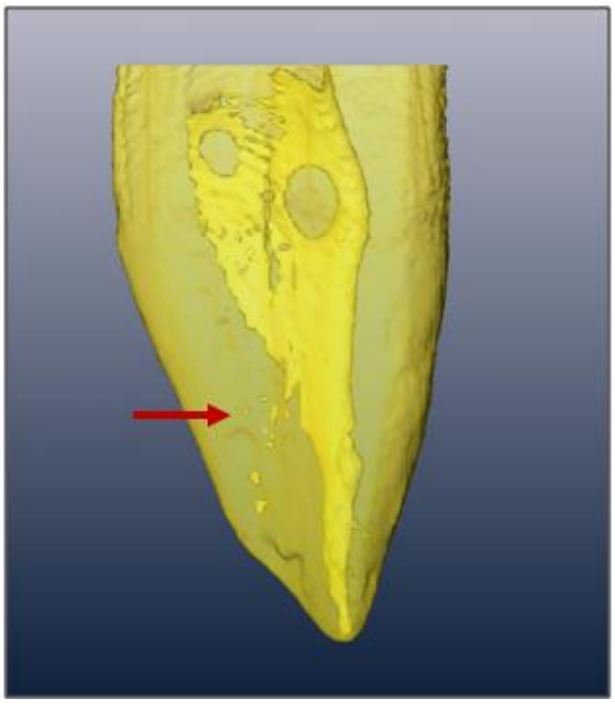


Figure 4.4j Representative mesiobuccal root showing two canals joined at coronal and middle level. Note lateral canal appears to be present but is not patent (arrow).

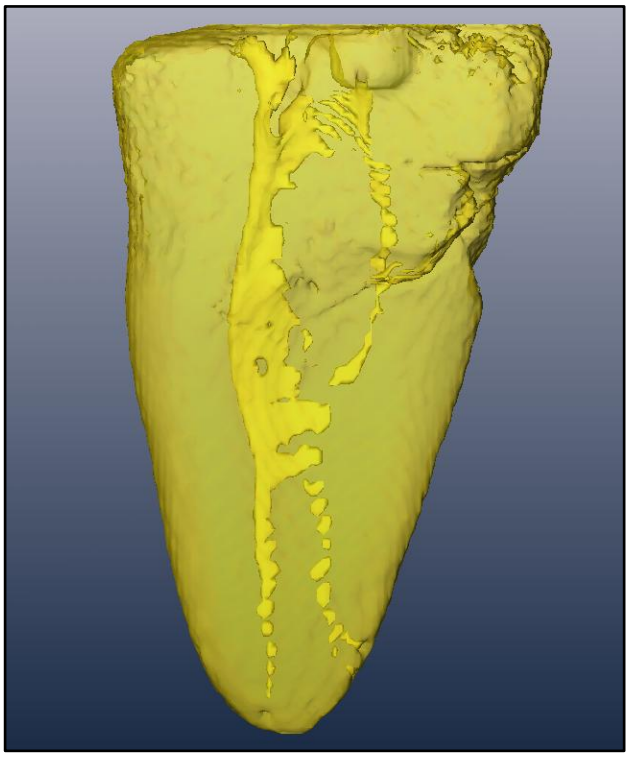


Figure 4.4k Representative mesiobuccal root showing two canals joining in the middle level, and then dividing apically.

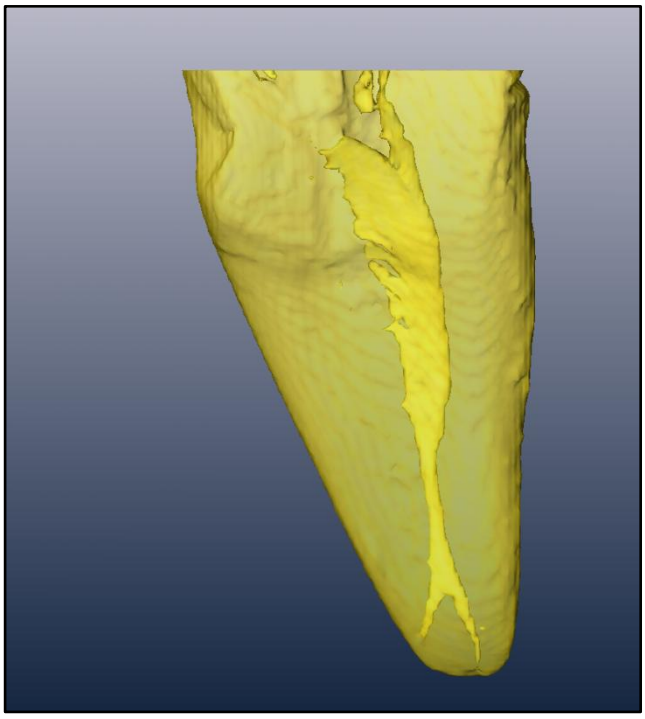


Figure 4.4l Mesiobuccal root with one canal. Variations present in the coronal and middle (fin) and apical levels (accessory canal present).

The results for evaluating the AlphaKite instrument on its ability to remove canal variations are outlined in Table 4.4. In eight roots, variations were not removed or instrumented (Figs. 4.4m, n). In one root variations were partially removed or instrumented. No roots showed complete instrumentation or removal of the variations.

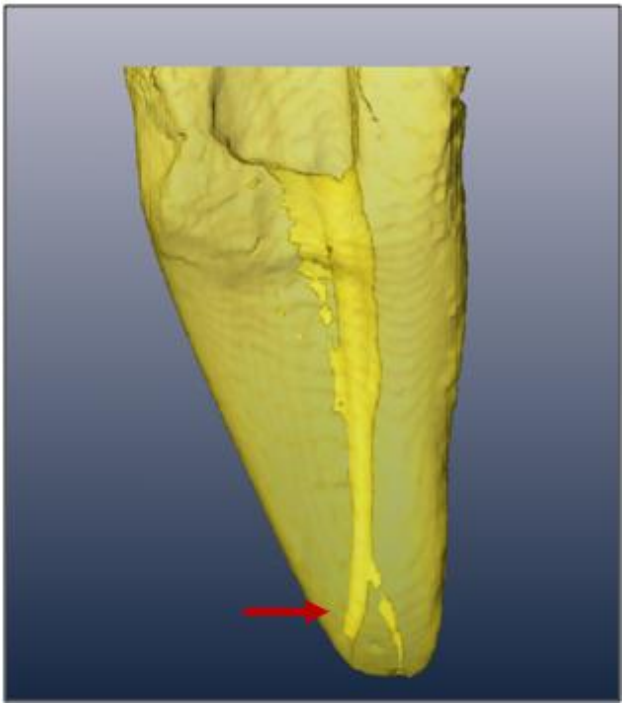


Figure 4.4m Mesiobuccal root showing canal in Figure 4.4l post-instrumentation with AlphaKite instruments, canal variations not removed. Preparation appeared to follow the accessory canal rather than the main canal (arrow).

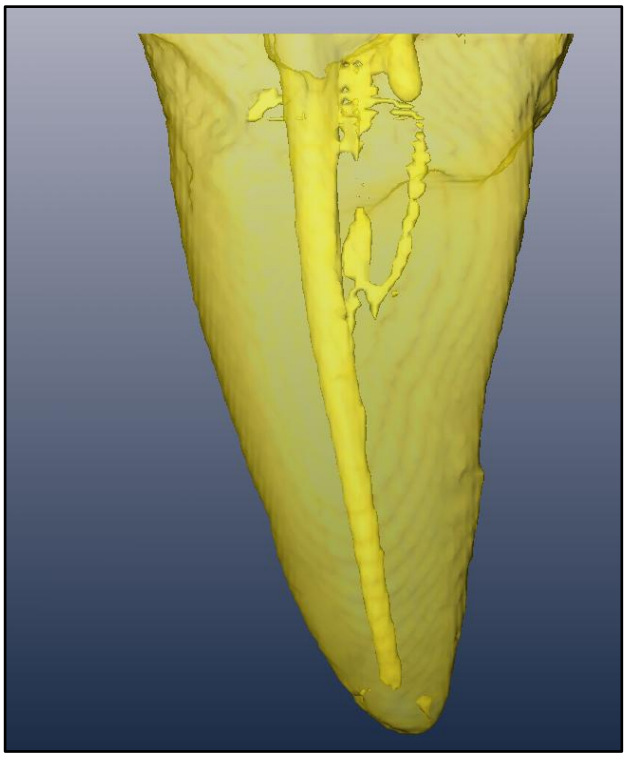


Figure 4.4n Representative mesiobuccal root of the canals in Figure 4.4i post-instrumentation with AlphaKite instruments. Note MB2 was not instrumented. The apical accessory canal and terminal portion of canal are absent from the image probably as a result of image artifacts or dentine debris filling the canals.

CHAPTER 5: DISCUSSION AND CONCLUSION

The present study was designed to determine the canal transportation and the centering ability of two nickel-titanium (NiTi) rotary systems BioRaCe (FKG, Switzerland) and AlphaKite (Komet, Germany). The study was set out with a second aim of evaluating the two systems on their ability to eradicate canal variations (e.g. lateral and accessory canals, fins and inter-canal communications) of the mesiobuccal root of first maxillary molars. It was hypothesized that both BioRaCe and AlphaKite instruments would produce well centered and tapered preparations with minimal canal transportation. It was also hypothesized that due to the complex anatomy of the mesiobuccal root of maxillary first molars, canal variations would be difficult to eradicate after canal preparation with either system.

5.1 Study design

A main objective of root canal preparation is to develop a shape that tapers from apical to coronal while maintaining the original canal shape and ensuring the smallest diameter is at the apical end-point (Thompson & Dummer 2000). A number of procedural errors can occur during the preparation including canal transportation, apical zip, elbow, ledge formation, perforation, file separation and canal blockage. BioRace and AlphaKite files used in the present study were designed to improve various aspects of the properties required for canal preparation instruments, including less canal transportation, fewer intra-canal file separations, and fewer procedural errors.

Several methodologies have been used to evaluate the final shape of root canal preparations such as the Bramante serial sectioning technique (Bramante *et al.* 1987) and examination using a stereomicroscope (Jung *et al.* 2005a). Sectioning, however,

has the disadvantage of loss of some parts of the specimen structure and therefore loss of data. Simulated root canals allow a high degree of reproducibility and standardization for root canal diameter, length and curve angle, but do not reflect the clinical situation. Additionally, the difference in hardness between resin and dentine may affect the cutting behaviour of the instruments. Radiographic assessment only gives a two-dimensional evaluation of the root canal and a cross-sectional image of the root canal is impossible to observe. A study design that allows for standardization and facilitates simulation of the clinical situation is desirable when evaluating the quality of root canal preparation. Micro-computed tomography allows increased precision and resolution to produce a three-dimensional image with no destruction of the sample. With this technique, it is possible to compare the anatomic structure of the root canal before and after instrumentation.

The present study evaluated root canal preparation using high-resolution tomography, or micro-CT, with a spatial resolution of 15.96-17.35 μm. Spatial resolution has improved continuously over time from 127 μm (Nielsen *et al.* 1995) to < 11 μm (Verma & Love 2011). However, an improvement in resolution is reflected by a long scanning time which adds to an already long reconstruction period. Due to these considerations the sample size for this study was set at 20 teeth. Despite the variations in the morphology of extracted teeth, attempts were made to ensure standardization of the experimental groups. The teeth in both BioRaCe and AlphaKite groups were balanced with respect to the angle of canal curvature based on initial radiographs.

5.2 Shaping ability

The results of the present investigation corroborate the findings of a great deal of the previous work on rotary NiTi instruments. Various studies have investigated rotary root canal preparations and they have shown that rotary NiTi instruments maintained the original canal shape even in extremely curved canals (Glosson *et al.*

1995, Short *et al.* 1997, Bryant *et al.* 1998a, Kum *et al.* 2000, Hülsmann *et al.* 2003a). The results confirm findings of previous studies concerning the ability of NiTi instruments to respect the original root canal curvature.

When comparing the shaping abilities of different root canal instruments, it is of importance to have similar tapers and similar apical preparation diameters (Bergmans *et al.* 2003). The manufacturer of BioRaCe recommends a final apical size of 35 or 40 when preparing the mesiobuccal root of upper molars. In the AlphaKite system, the size of the instrument is chosen according to the root canal morphology of the pre-operative status. All canals in this study were therefore prepared to an apical size of 35 for both BioRaCe and AlphaKite systems to assure equal conditions in the two groups.

There have been few studies published on the shaping ability of BioRaCe instruments. BioRaCe instruments present the same physical characteristics of RaCe instruments such as non-cutting safety tips, sharp cutting edges with a triangular section, alternating cutting edges to avoid self-threading, and both instruments are treated electro-chemically to obtain smoother surfaces. Schäfer & Vlassis (2004b) showed that RaCe instruments maintained working length well in curved canals. Yoshimine *et al.* (2005) showed that RaCe instruments did not create any canal transportation. The study by Bonaccorso *et al.* (2009) compared the shaping ability of four NiTi rotary instruments: ProTaper, Mtwo, BioRaCe, and BioRaCe + S-Apex in simulated canals with an S-shaped curvature. S-Apex files are NiTi rotary instruments with an inverted taper, designed to create a glide path and to enlarge the apical part of the canals. ProTaper instruments resulted in marked straightening of the canals whereas BioRaCe + S-Apex instruments removed significantly less resin at the inner side of the coronal curvature than all other instruments. BioRaCe was comparable to Mtwo and BioRaCe + S-Apex at the inner side of the apical curvature. In the BioRaCe group canals were enlarged to size 40. BioRaCe was the only

instrument showing no fracture and no deformation. The use of BioRaCe seemed to be safe because the incidence of canal aberrations was low. Similarly, in the present study, BioRaCe instruments resulted in minimal canal transportation in all areas of a curved canal and none of the instruments fractured. In contrast, Uyanik *et al.* (2006) showed that RaCe files significantly transported the original canal pathway, compared to Hero Shaper and ProTaper. The authors suggested that the unfavourable results reported for RaCe might be due to stainless steel instruments included in the preparation sequence.

There have been no studies on the shaping ability of AlphaKite instruments. The Alpha System was introduced into the market in 2005 before AlphaKite instruments. The instruments in both systems share similar properties except for the cross-section design. In the Alpha System, the instruments designed for coronal flaring have a kite-shaped cross-section and the remaining instruments have a five-edged pentagon cross-section. In the AlphaKite instruments all of the instruments have a kite-shaped cross-section. Limited data exist on the performance of the Alpha System. Vaudt *et al.* (2009), compared the Alpha System with ProTaper and stainless steel hand instruments. The Alpha System revealed significantly less apical straightening compared with the other instruments. The different designs of these NiTi systems could have influenced the observed outcomes. ProTaper Universal files have multiple and increased tapers (up to 11%) compared with the Alpha files presenting a less and constant taper (2%). An increasing taper is associated with increased cross-section areas and decreased flexibility of the files that could cause straightening and root canal aberration during preparation (Bergmans *et al.* 2001). Within the limitations of the present study, BioRaCe and AlphaKite instruments prepared canals well, maintained the canal shape with minimal canal transportation and were relatively safe.

Canals shaped by BioRaCe were usually transported toward the inside of the curve in the coronal section (total of 7, n=10). In the middle third of the canals, 6 canals were transported toward the inside of the curve, and one canal showed zero transportation. In the apical third all canals were transported toward the outside of the curve. There was a statistically significant difference in the amount of transportation between the coronal and apical levels. The larger amount of transportation at the coronal levels (-0.12 ± 0.19) versus (-0.01 ± 0.09) at the middle or (+0.06 ± 0.05) at the apical levels may be due to the design of the instruments, BR0, BR1 and BR3, with tapers 0.08, 0.05, 0.06 respectively, in which the tips do not touch the canal walls when the instruments are at full working length. Some canal transportation may be a good thing, in cases where over-enlargement of the canal occurs, especially at the coronal levels with non-round cross-sections, and to allow access of the instruments to the apical foramen to minimize the risk of apical canal transportation. Apical canal transportation can leave parts of the original root canal uninstrumented and can be detrimental to the success of root canal therapy. Sjögren *et al.* (1990) stated that the apical canal may harbor a significant amount of micro-organisms that would maintain periradicular inflammation. Simon (1994) considered the apical 3 mm of the root canal system to be a "critical zone" in the management of infected canals.

In the AlphaKite system, five canals were transported toward the inside of the curve at the coronal and middle levels (n=9), and eight of the nine canals were transported toward the outside of the curve at the apical level, with no significant difference in the amount of transportation across the three levels. Transportation with AlphaKite instruments at the coronal and apical levels was smaller than with BioRaCe instruments. The difference in transportation between the two systems, however, was not statistically significant at any level. It is debatable whether or not the small amount of transportation that occurred in both systems is clinically relevant. The

occurrence of apical transportation, nevertheless, is a factor that negatively influences the apical seal compared to ideally prepared canals (Wu *et al.* 2000).

The results show that the direction of transportation in the apical area is mainly toward the outside curvature. This finding is consistent with previous studies (Peters *et al.* 2001b, Taşdemir *et al.* 2005, Merrett *et al.* 2006). Pasternak-Junior *et al.* (2009), however, reported transportation to the inner side of the curvature with the use of size 35 RaCe instruments with 0.02 taper. The authors reported that the probable reason lies in the superelasticity of the instruments allowing them to follow the canal curvature. The occurrence of deviations can therefore depend on factors other than the curvature, such as the instrument design, the physical properties of the alloy and the technical instrumentation (Kosa *et al.* 1999, Peters *et al.* 2001b).

It should be noted that the transportation measured in this study was the transportation that occurred toward the thinnest portion of the tooth in the plane of greatest canal curvature, rather than the total amount of transportation (Gambill *et al.* 1996). Transportation results give an indication of how much material was removed with respect to the ideal preparation (where '0' transportation occurs), and indicate the direction of dentine removal (toward the inner or outer side of the curve). Centering ability indicates how well a technique removed dentine equally over the prepared area. For example, perfect centering implies that equal amounts of dentine were removed from all portions of the canal. If the centering ratio was zero, dentine was removed from one part of the canal only.

The relevance of canal centering during instrumentation pertains primarily to canal transportation (Knowles *et al.* 1996). Neither of the systems used in the study had perfect centering. Both systems showed moderate centering abilities at most root levels. AlphaKite system showed good centering ability at the apical part of the canal whereas BioRaCe system showed poor centering ability at the coronal part of the canal. There were however, no significant differences in the centering ratios between

the two systems, or across the three levels for each system. If the instrument could remain centered and avoid the dangers of ledging, zipping and apical perforations, a more predictable endodontic therapy outcome could be expected. The good centering ability at the apical level in AlphaKite system implies that dentine was removed in a more uniform pattern from all canal walls. This good centering ability and minimal transportation in the apical part is in contrast to previous studies on earlier rotary instruments that showed that the inner wall of a canal in the apical portion received no or minimal preparation compared to the outer wall (Ayar & Love 2004). Although not tested in the present study, this would suggest that the debridement of an infected canal may be adequately accomplished by the AlphaKite system.

The worst centering ratio was observed at the coronal level after preparation using the BioRaCe system. It could be that the BioRaCe instrument with 0.08 taper used in the coronal aspect is less flexible than the AlphaKite instrument with similar taper used in the upper third of the canal. According to the manufacturer's recommendations, BioRaCe instruments with tapers 0.05, 0.04 and 0.06 are used to full working length except in canals with severe apical curvatures where the extended kit is recommended with instruments that have 0.02 taper. In the present study, AlphaKite instruments with 0.02 taper were used in the apical region, 0.04 taper in the middle region and 0.06 taper for the upper third of the canal. The smaller tapers used with AlphaKite instruments compared to BioRaCe may have resulted in the better centering ratios at all levels, but the difference was not statistically significant.

The increased flexibility of NiTi instruments is able to explain their good centering ability. A number of studies have shown that the centering ratio of rotary NiTi instruments was better than stainless steel files (Zmener & Banegas 1996, Short *et al.*

1997, Portenier *et al.* 1998, Schäfer & Florek 2003). The superior flexibility reduces the risk of canal transportation during enlargement of curved canals (Schäfer *et al.* 2003).

Another factor that could contribute to the moderately centered preparations could lie in the design of the active part of the BioRaCe instruments, with alternating cutting edges along the file length. This design is due to alternating twisted and untwisted segments. The manufacturer claims that alternating cutting edges prevent the instrument from screwing into the root canal and reduce intraoperative torque values (Schäfer & Vlassis 2004b, Paqué *et al.* 2005b).

The cutting ability of root canal instruments is a complex interrelationship of different parameters such as cross-sectional design, helical and rake angle, metallurgical properties, and surface treatment of the instruments (Hülsmann *et al.* 2005). Some surface engineering techniques (e.g., ion implantation and physical vapor deposition [PVD] coating) are suitable for use to improve the surface hardness and cutting efficiency of NiTi instruments (Schäfer 2002). Alpha and AlphaKite instruments are the only commercially available PVD-coated rotary NiTi instruments. The results of a recent study, however, revealed no significant influence of the PVD coating surface on the cutting efficiency. The Alpha System files showed a significantly lower cutting efficiency compared with Mtwo, RaCe, and Flexmaster (2008). In the latter study, the authors concluded that cross-sectional design seems to be a more decisive parameter concerning the cutting efficiency of rotary NiTi instruments than a surface treatment. Alpha instruments have a pentagon cross-section whereas AlphaKite instruments have a kite-shaped cross-section. It would be of interest to initiate further studies evaluating solely the effect of PVD coatings on the cutting efficiency of rotary NiTi instruments with different cross-sectional designs.

The present study demonstrated that two different mechanical designs of NiTi rotary instruments produced similar results with minimal transportation. Cross-sectional

configuration (design and area) influences bending properties of instruments (Schäfer *et al.* 2003). Some of the other factors that may have contributed to minimal transportation in this study could have been the preliminary enlargement of canals to a size 15 K-file and that each system was used according to their manufacturers' recommendations.

The shaping ability of an instrument and the prevention of aberrations depend on factors other than the alloy type, or taper and size of instrument. The type of the cutting tip and geometry of the cross-section also affect the shaping ability. Both systems used in the study are characterized by a non-cutting safety tip. The use of instruments with sharp cutting tips predisposes to transportation and creates defects during preparation (Powell *et al.* 1986, 1988, Griffiths *et al.* 2001). BioRaCe instruments possess sharp cutting edges with a triangular cross-section with no radial lands. Instruments with actively cutting blades display better results in terms of canal cleanliness than files with radial lands (Schäfer & Vlassis 2004b, Schäfer *et al.* 2006b). The active cutting edges seem to cut and remove both dentine chips and pulp remnants, whereas radial lands tend to burnish the cut dentine onto the root canal wall or even push debris inside the dentinal tubules (Hülsmann *et al.* 2005). Chip removal capability also determines the efficiency of rotary instruments because the removal of cut dentine chips is important to reduce clogging of the cutting blades (Bergmans *et al.* 2001). The manufacturer of AlphaKite claims that the kite-shaped design with an active cutting angle and three more supporting blades provides large chip spaces that guarantee optimum evacuation of debris from the root canal. No published literature exists about the kite-shaped design feature up to now. Schäfer & Oitzinger (2008) reported that RaCe instruments have great chip capability and great chip space. It may be speculated that BioRaCe and AlphaKite instruments have comparable large chip removal capability and at the same time large chip space that prevents apical blockage and thus result in minimal transportation.

Other factors that may have contributed to the minimal transportation observed in the study were operator-related. All teeth were prepared by an experienced operator in rotary instruments. It has been shown that forcing an instrument into the root canal increases the incidence of aberrations and procedural errors (Jafarzadeh & Abbott 2007). The use of each rotary instrument was followed by copious amount of sodium hypochlorite irrigation and the debris was removed from the flutes after each canal preparation. Although evidence regarding canal transportation when using lubricants is limited (Hülsmann *et al.* 2003c), enhanced lubrication permits easier file insertion, reduces stress to the file, and assists with removal of debris. Finally, in the present study few of the specimens had severe canal curvatures. Studies have showed that root canals with a large angle and a small radius of curvature can hardly be enlarged without any transportation, irrespective of whether rotary NiTi or stainless-steel hand instruments were used (Dummer *et al.* 1998).

The design of the present study minimized the potential for instrument fracture. The operator was experienced and the files were routinely examined after each use and were discarded after preparing five roots. Both systems were used according to manufacturer's guidelines and were driven by electric motors with torque control and constant speed. During the course of this study, only one instrument, 0.02 taper size 25 AlphaKite instrument, separated. To date, no data is available on the torsional property of AlphaKite files. It has been shown, however, that the electropolishing surface treatment of BioRaCe endodontic instruments significantly increases their cyclic fatigue resistance (Lopes *et al.* 2010). Electropolishing is a method of surface finishing used by manufacturers to remove surface defects that might remain after the machining process (Lopes *et al.* 2010). Nevertheless, no conclusions can be drawn regarding propensity of AlphaKite instruments to fracture more than BioRaCe.

5.3 Eradication of canal variations

The results show that none of the systems completely eradicated canal variations of the mesiobuccal root of the maxillary first molar. BioRaCe instruments partially removed canal variations in four canals (n=10) whereas AlphaKite instruments partially removed canal variations in one canal (n=9).

Comparing pre- and post-instrumentation images of the canals revealed that the majority of canal variations were uninstrumented after preparation. In general, the amount of prepared root canal surface seemed to be independent of the instrument system used but was significantly affected by pre-operative canal anatomy. This is in agreement with the study of Peters *et al.* (2001b), in which 35-40% of the walls of maxillary molar buccal root canals remained untouched when enlarged up to instruments with size 40 to the working length.

Rotary instrumentation produces round or oval cross-sections. Theoretically, non-round canal cross-sections with variations such as fins and recesses may be more completely prepared with filing movements compared with a rotary technique. It would be of interest to initiate further quantitative analysis of the pre and postoperative cross-sections to confirm the percentage of uninstrumented canal walls at the three root levels. The study by Vaudt *et al*. (2009) reported that in the apical cross-sections the Alpha System resulted in significantly less uninstrumented canal walls compared with stainless-steel files.

Results of this study add to the ongoing debate as to which size a root canal should be prepared to apically. The debate began more than 30 years ago (Kerekes & Tronstad 1977) and is still unresolved (Mickel *et al.* 2007). Manufacturers of BioRaCe claim that the apical third of the canals must be instrumented to certain minimum sizes in order to remove enough microbes from the root canal. They suggest that the mesiobuccal root of maxillary first molars must be prepared to a size 35 or 40. The

instrumentation of the apical third to a larger size incorporates more anatomical irregularities and provides more irrigant exchange in the apical third (Wu & Wesselink 1995). On the other hand, wider apical preparations might result in some canal straightening and undesirable weakening of the tooth structure (Peters 2004). Canal variations in the present study were mostly not eradicated after preparation with both systems. This suggests that simple guidelines in terms of apical size do not comply with the varieties in root anatomy; therefore each canal should be prepared individually.

The results of this study indicate that BioRaCe and AlphaKite instruments have good shaping efficiency. Nevertheless, neither of the systems was able to completely eradicate canal variations. Viable microbes may penetrate deep into the dentinal tubules. Bacteria and necrotic debris may be present in canal variations. Since mechanical removal of all of the potentially infected dentine is impossible (Byström & Sundqvist 1981), the need for efficient chemical irrigation (in addition to the shaping regimen) and intracanal medicaments to clean the root canals effectively is clearly highlighted.

5.4 Study limitations and suggestions for future work

The long process of scanning and reconstructing images, together with time constraints limited the study sample size to 20 teeth. The results showed that both instruments produced moderately well centered canals with minimal transportation, and both systems were unable to completely eradicate canal variations. A larger sample size will compensate for anatomical variables and may show if there are differences between the two systems. It is also important to be aware of possible sources of errors to avoid overinterpretation of three-dimensionally reconstructed images (Mol 1999). However, on the basis of this work, both instruments prepared canals to acceptable good clinical standards. It would be interesting to do studies on BioRaCe and AlphaKite instruments and compare them with previously reported

results obtained from earlier rotary NiTi instruments under identical experimental conditions.

Further studies on BioRaCe and AlphaKite are required to focus on other criteria to assess the quality of canal preparation such as cleaning ability, safety issues, working time, handling and cost. Three-dimensional analyses can be further used to assess smoothness, flow characteristics and taper of the enlarged canals. Additional studies can be done to calculate the differences in dentine volume removed and proportions of unchanged areas after preparation using specially developed software.

Clinical studies assessing the effects of different instruments or instrumentation techniques are scarce. Future studies can be initiated to assess the impact of minimal canal transportation on the outcome of endodontic therapy.

5.5 Conclusion

The results of the present investigation confirm the results of previous studies on different rotary nickel-titanium instruments concerning their ability to maintain the original shape of curved canals. Within the limitations of this present study, BioRaCe and AlphaKite instruments prepared curved canals with minimal transportation and were relatively safe. Both instruments produced moderately well centered preparations.

The shaping efficiency of both systems could be attributed to the high elasticity characteristics of the instruments that resulted in minor root canal transportation. In addition to the flexibility of nickel-titanium instruments, other factors such as cross-section design of the instruments and geometry, and the instrumentation technique used, play important roles in reducing canal aberrations.

The study confirmed the complex anatomy of the mesiobuccal root of maxillary first molars. Within the limitations of the present *ex vivo* study, the experimental results

suggest that none of the rotary systems were able to effectively eradicate canal variations of the mesiobuccal root. This can alter the treatment outcome because the cleaning of all spaces, including variations such as inter-canal communications, fins, apical deltas and accessory and lateral canals is a very important phase during endodontic therapy. The role of chemical disinfection of the canal is therefore emphasized.

New research tools like micro-computed tomography offer great potential for accurate evaluation of endodontic procedures, supported by a unique combination of non-destructiveness of the samples tested. Images of the canals can be easily visualized in three-dimensions and conclusions can be drawn with acceptable clinical validity. The sample size in this study was small but the data obtained showed that both systems have good shaping abilities with comparable results. Additional studies are required to further evaluate the quality of canal preparation with BioRaCe and AlphaKite instruments.

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APPENDIX 1: ABSTRACT FOR POSTER PRESENTATION

- Abstract accepted for poster presentation at the 15th biennial congress of the European Society of Endodontology, September 2011 [will be published in International Endodontic Journal].

Root canal preparation with two different rotary systems: comparative study assessed by micro-computed tomography

A O Al-dameh, R M Love

Aim To evaluate root canal transportation using micro-computed tomography (micro-CT) after canal preparation *ex vivo* with two nickel-titanium rotary instruments.

Methodology Mesiobuccal roots of 20 maxillary first molars with similar angles of curvature were divided randomly into two groups and scanned using a SkyScan 1172 micro-CT scanner (SkyScan, Belgium). Root canals were then prepared with AlphaKite (Komet, Germany) or BioRaCe instruments (FKG Dentaire, Switzerland). The prepared roots were re-scanned and cross-sectional images of the pre- and post-instrumentation scans were reconstructed using the Skyscan reconstruction software. Cross-sectional images were compared and the amount of transportation was assessed quantitatively by measuring the shortest distance from the edge of the uninstrumented canal to the periphery of the root (mesial and distal) and then comparing this with the same measurements obtained from the instrumented images. A negative result indicated transportation toward the distal surface of the root (inner curvature), a positive result toward the mesial surface (outer curvature), and nil, the absence of transportation. Student *t*-tests and ANOVA tests were used for statistical analysis.

Results The average canal transportation with BioRaCe instruments in the apical, middle and coronal thirds were +0.06 ± 0.05, -0.01 ± 0.09 and -0.12 ± 0.19 mm, respectively, with a significant difference ($P < 0.05$) in the amount of transportation between the apical and coronal levels. Average canal transportation with AlphaKite instruments in the apical, middle and coronal thirds were +0.03 ± 0.03, -0.04 ± 0.10 and -0.05 ± 0.22 mm, respectively, with no significant difference between the groups ($P > 0.05$). There was no statistically significant difference between the systems in regard to canal transportation across all levels ($P > 0.05$).

Conclusions Within the limitations of this *ex vivo* study, there were few differences between the two instrumentation techniques used. Both techniques produced minimal canal transportation.

APPENDIX 2: RAW DATA

BioRaCe Data (first set)

		X1	X2	Y1	Y2
TOOTH4	CORONAL 1	2.06	1.91	1.34	1.21
TOOTH4	CORONAL 2	1.77	1.78	1.6	1.34
TOOTH4	CORONAL 3	1.66	1.69	1.23	0.9
TOOTH4	MIDDLE 1	1.6	1.56	1.07	0.84
TOOTH4	MIDDLE 2	1.5	1.45	1.03	0.9
TOOTH4	MIDDLE 3	1.39	1.36	0.87	0.82
TOOTH4	MIDDLE 4	1.39	1.35	0.86	0.81
TOOTH4	APICAL 1	1.36	1.19	0.87	0.78
TOOTH4	APICAL 2	1.05	0.85	0.87	0.82
TOOTH4	APICAL 3	0.69	0.65	0.73	0.67
TOOTH 12	CORONAL 1	1.79	1.69	1.26	1.14
TOOTH 12	CORONAL 2	1.67	1.56	1.2	0.86
TOOTH 12	CORONAL 3	1.54	1.5	1.23	0.9
TOOTH 12	MIDDLE 1	1.42	1.41	1.2	0.9
TOOTH 12	MIDDLE 2	1.4	1.42	1.35	1.06
TOOTH 12	MIDDLE 3	1.45	1.36	1.32	1.19
TOOTH 12	MIDDLE 4	1.46	1.28	1.34	1.33
TOOTH 12	APICAL 1	1.18	1	1.49	1.48
TOOTH 12	APICAL 2	0.64	0.69	0.78	0.75
TOOTH 12	APICAL 3	0.85	0.63	0.64	0.64
TOOTH 20	CORONAL 1	2	1.72	0.73	0.78
TOOTH 20	CORONAL 2	1.67	1.51	1.22	1.17
TOOTH 20	CORONAL 3	1.41	1.4	1.19	0.9
TOOTH 20	MIDDLE 1	1.23	1.23	0.96	0.65
TOOTH 20	MIDDLE 2	1.15	1.08	0.85	0.67
TOOTH 20	MIDDLE 3	1.04	0.92	0.86	0.78
TOOTH 20	MIDDLE 4	1.03	0.93	0.7	0.7
TOOTH 20	APICAL 1	0.97	0.84	0.76	0.67
TOOTH 20	APICAL 2	0.78	0.72	0.77	0.72
TOOTH 20	APICAL 3	0.51	0.45	0.55	0.54
TOOTH 10	CORONAL 1	1.92	1.63	0.64	0.63
TOOTH 10	CORONAL 2	1.67	1.5	1.07	1.03
TOOTH 10	CORONAL 3	1.5	1.43	0.92	0.95

TOOTH 10	MIDDLE 1	1.35	1.36	1.02	0.71
TOOTH 10	MIDDLE 2	1.28	1.22	0.88	0.8
TOOTH 10	MIDDLE 3	1.24	1.16	0.79	0.81
TOOTH 10	MIDDLE 4	1.19	1.08	0.87	0.81
TOOTH 10	APICAL 1	1.13	0.89	0.92	0.79
TOOTH 10	APICAL 2	1.06	0.72	0.96	0.78
TOOTH 10	APICAL 3	0.78	0.45	0.63	0.54
TOOTH 8	CORONAL 1	1.2	1.24	1.4	1.04
TOOTH 8	CORONAL 2	1.13	1.13	1.21	0.9
TOOTH 8	CORONAL 3	1.01	0.97	1.13	0.92
TOOTH 8	MIDDLE 1	0.95	0.82	1.16	0.96
TOOTH 8	MIDDLE 2	0.9	0.76	1.06	1.01
TOOTH 8	MIDDLE 3	0.92	0.68	0.91	1.08
TOOTH 8	MIDDLE 4	0.8	0.64	1.02	1
TOOTH 8	APICAL 1	0.79	0.63	1	0.94
TOOTH 8	APICAL 2	0.78	0.66	1.07	0.97
TOOTH 8	APICAL 3	0.68	0.55	0.89	0.67
TOOTH 18	CORONAL 1	1.79	1.45	1.01	0.67
TOOTH 18	CORONAL 2	1.57	1.3	1.07	0.67
TOOTH 18	CORONAL 3	1.25	1.12	0.95	0.74
TOOTH 18	MIDDLE 1	1.18	1.14	0.93	0.88
TOOTH 18	MIDDLE 2	1.13	1.09	0.98	0.93
TOOTH 18	MIDDLE 3	1.07	1.05	0.96	1
TOOTH 18	MIDDLE 4	1.03	1.06	1.03	1.02
TOOTH 18	APICAL 1	1.08	0.88	1.11	1.05
TOOTH 18	APICAL 2	0.84	0.7	0.96	0.83
TOOTH 18	APICAL 3	0.61	0.58	0.65	0.54
TOOTH 1	CORONAL 1	1.33	1.29	1.19	0.5
TOOTH 1	CORONAL 2	1.22	1.14	0.89	0.5
TOOTH 1	CORONAL 3	1.12	1.03	0.8	0.5
TOOTH 1	MIDDLE 1	1	0.83	0.68	0.57
TOOTH 1	MIDDLE 2	1.04	0.76	0.76	0.58
TOOTH 1	MIDDLE 3	0.9	0.7	0.67	0.61
TOOTH 1	MIDDLE 4	0.86	0.69	0.68	0.59
TOOTH 1	APICAL 1	0.77	0.7	0.56	0.48
TOOTH 1	APICAL 2	0.68	0.5	0.44	0.42
TOOTH 1	APICAL 3	0.19	0.19	0.05	0.08
TOOTH 11	CORONAL 1	1.79	1.63	1.1	1.03
TOOTH 11	CORONAL 2	1.48	1.5	1.14	0.79
TOOTH 11	CORONAL 3	1.38	1.31	1.07	0.74

TOOTH 11	MIDDLE 1	1.21	1.23	0.91	0.82
TOOTH 11	MIDDLE 2	1.25	1.19	1.04	0.92
TOOTH 11	MIDDLE 3	1.23	1.11	1.19	0.97
TOOTH 11	MIDDLE 4	1.18	1.02	1.01	0.88
TOOTH 11	APICAL 1	0.98	0.88	0.8	0.7
TOOTH 11	APICAL 2	0.86	0.76	0.69	0.62
TOOTH 11	APICAL 3	0.63	0.41	0.44	0.36
TOOTH 14	CORONAL 1	2.04	1.64	1.1	1.23
TOOTH 14	CORONAL 2	1.79	1.52	1.28	1.12
TOOTH 14	CORONAL 3	1.43	1.35	1.09	0.79
TOOTH 14	MIDDLE 1	1.22	1.15	1.04	0.74
TOOTH 14	MIDDLE 2	1.13	1.05	1	0.86
TOOTH 14	MIDDLE 3	1.01	0.93	0.94	0.87
TOOTH 14	MIDDLE 4	1.05	0.94	0.95	0.94
TOOTH 14	APICAL 1	0.99	0.93	1.12	0.99
TOOTH 14	APICAL 2	1.02	0.9	1.03	0.95
TOOTH 14	APICAL 3	0.82	0.41	0.98	0.9
TOOTH 16	CORONAL 1	1.55	1.5	1.23	0.88
TOOTH 16	CORONAL 2	1.66	1.33	1.34	0.86
TOOTH 16	CORONAL 3	1.41	1.2	1.47	0.93
TOOTH 16	MIDDLE 1	1.26	1.02	1.27	1.03
TOOTH 16	MIDDLE 2	1.06	0.86	1.11	0.99
TOOTH 16	MIDDLE 3	1.02	0.75	0.95	0.86
TOOTH 16	MIDDLE 4	0.89	0.72	0.82	0.71
TOOTH 16	APICAL 1	0.77	0.61	0.74	0.61
TOOTH 16	APICAL 2	0.64	0.48	0.66	0.48
TOOTH 16	APICAL 3	0.42	0.32	0.45	0.35

BioRaCe Data (second set)

		X1	**X2**	**Y1**	**Y2**
TOOTH4	CORONAL 1	2.08	1.93	1.34	1.18
TOOTH4	CORONAL 2	1.77	1.76	1.56	1.32
TOOTH4	CORONAL 3	1.62	1.63	1.18	0.93
TOOTH4	MIDDLE 1	1.57	1.54	1.11	0.85
TOOTH4	MIDDLE 2	1.49	1.43	1.04	0.9
TOOTH4	MIDDLE 3	1.38	1.36	0.89	0.83
TOOTH4	MIDDLE 4	1.38	1.36	0.84	0.79
TOOTH4	APICAL 1	1.35	1.18	0.87	0.82
TOOTH4	APICAL 2	1.03	0.87	0.9	0.8

TOOTH4	APICAL 3	0.68	0.67	0.71	0.68
TOOTH 12	CORONAL 1	1.8	1.68	1.26	1.13
TOOTH 12	CORONAL 2	1.67	1.59	1.2	0.83
TOOTH 12	CORONAL 3	1.51	1.5	1.25	0.89
TOOTH 12	MIDDLE 1	1.42	1.42	1.22	0.89
TOOTH 12	MIDDLE 2	1.42	1.43	1.34	1.04
TOOTH 12	MIDDLE 3	1.43	1.38	1.34	1.22
TOOTH 12	MIDDLE 4	1.47	1.27	1.37	1.31
TOOTH 12	APICAL 1	1.19	1	1.44	1.47
TOOTH 12	APICAL 2	0.66	0.74	0.8	0.75
TOOTH 12	APICAL 3	0.84	0.59	0.65	0.61
TOOTH 20	CORONAL 1	1.98	1.71	0.7	0.79
TOOTH 20	CORONAL 2	1.63	1.51	1.23	1.18
TOOTH 20	CORONAL 3	1.39	1.39	1.14	0.89
TOOTH 20	MIDDLE 1	1.26	1.24	0.9	0.65
TOOTH 20	MIDDLE 2	1.17	1.08	0.83	0.67
TOOTH 20	MIDDLE 3	1.04	0.93	0.85	0.77
TOOTH 20	MIDDLE 4	1.03	0.93	0.69	0.71
TOOTH 20	APICAL 1	0.97	0.85	0.74	0.69
TOOTH 20	APICAL 2	0.79	0.72	0.74	0.72
TOOTH 20	APICAL 3	0.51	0.46	0.55	0.54
TOOTH 10	CORONAL 1	1.91	1.64	0.58	0.64
TOOTH 10	CORONAL 2	1.64	1.51	1.03	1.02
TOOTH 10	CORONAL 3	1.5	1.44	0.95	0.91
TOOTH 10	MIDDLE 1	1.34	1.34	1	0.76
TOOTH 10	MIDDLE 2	1.3	1.22	0.9	0.79
TOOTH 10	MIDDLE 3	1.24	1.16	0.79	0.79
TOOTH 10	MIDDLE 4	1.18	1.08	0.9	0.8
TOOTH 10	APICAL 1	1.13	0.92	0.93	0.8
TOOTH 10	APICAL 2	1	0.73	0.94	0.79
TOOTH 10	APICAL 3	0.78	0.47	0.63	0.54
TOOTH 8	CORONAL 1	1.19	1.24	1.4	1.04
TOOTH 8	CORONAL 2	1.12	1.11	1.22	0.85
TOOTH 8	CORONAL 3	1.01	0.96	1.13	0.92
TOOTH 8	MIDDLE 1	0.97	0.81	1.16	0.98
TOOTH 8	MIDDLE 2	0.9	0.75	1.07	1.01
TOOTH 8	MIDDLE 3	0.92	0.69	0.94	1.03
TOOTH 8	MIDDLE 4	0.8	0.63	1.02	1
TOOTH 8	APICAL 1	0.82	0.64	1	0.9
TOOTH 8	APICAL 2	0.78	0.66	1.08	0.97

TOOTH 8	APICAL 3	0.62	0.53	0.94	0.67
TOOTH 18	CORONAL 1	1.76	1.45	0.94	0.67
TOOTH 18	CORONAL 2	1.49	1.29	1.03	0.67
TOOTH 18	CORONAL 3	1.2	1.12	0.95	0.71
TOOTH 18	MIDDLE 1	1.19	1.13	0.91	0.88
TOOTH 18	MIDDLE 2	1.06	1.06	0.97	0.96
TOOTH 18	MIDDLE 3	1.09	1.07	0.95	0.97
TOOTH 18	MIDDLE 4	1.09	1.06	1.07	1.04
TOOTH 18	APICAL 1	1.06	0.87	1.1	1.01
TOOTH 18	APICAL 2	0.8	0.73	0.93	0.84
TOOTH 18	APICAL 3	0.62	0.54	0.65	0.54
TOOTH 1	CORONAL 1	1.33	1.24	1.16	0.5
TOOTH 1	CORONAL 2	1.22	1.15	0.84	0.47
TOOTH 1	CORONAL 3	1.1	1.02	0.84	0.49
TOOTH 1	MIDDLE 1	1.02	0.84	0.7	0.6
TOOTH 1	MIDDLE 2	1	0.75	0.77	0.6
TOOTH 1	MIDDLE 3	0.92	0.72	0.68	0.62
TOOTH 1	MIDDLE 4	0.85	0.69	0.67	0.59
TOOTH 1	APICAL 1	0.78	0.69	0.55	0.5
TOOTH 1	APICAL 2	0.67	0.48	0.45	0.4
TOOTH 1	APICAL 3	0.18	0.19	0.05	0.08
TOOTH 11	CORONAL 1	1.81	1.67	1.09	1.01
TOOTH 11	CORONAL 2	1.5	1.48	1.12	0.77
TOOTH 11	CORONAL 3	1.36	1.3	1.08	0.76
TOOTH 11	MIDDLE 1	1.2	1.22	0.92	0.81
TOOTH 11	MIDDLE 2	1.21	1.18	1.04	0.91
TOOTH 11	MIDDLE 3	1.21	1.11	1.18	0.99
TOOTH 11	MIDDLE 4	1.18	1.01	1.01	0.87
TOOTH 11	APICAL 1	0.97	0.87	0.8	0.67
TOOTH 11	APICAL 2	0.85	0.76	0.7	0.63
TOOTH 11	APICAL 3	0.63	0.44	0.44	0.36
TOOTH 14	CORONAL 1	2.05	1.65	1.11	1.25
TOOTH 14	CORONAL 2	1.79	1.53	1.33	1.1
TOOTH 14	CORONAL 3	1.43	1.31	1.1	0.77
TOOTH 14	MIDDLE 1	1.25	1.17	1.04	0.74
TOOTH 14	MIDDLE 2	1.15	1.04	1	0.86
TOOTH 14	MIDDLE 3	1.05	0.94	0.94	0.86
TOOTH 14	MIDDLE 4	1.03	0.95	0.94	0.95
TOOTH 14	APICAL 1	0.99	0.93	1.09	0.97
TOOTH 14	APICAL 2	1.01	0.87	1.04	0.94

TOOTH 14	APICAL 3	0.84	0.4	0.95	0.9
TOOTH 16	CORONAL 1	1.55	1.51	1.21	0.86
TOOTH 16	CORONAL 2	1.66	1.33	1.29	0.87
TOOTH 16	CORONAL 3	1.42	1.19	1.46	0.94
TOOTH 16	MIDDLE 1	1.26	1.02	1.25	1.03
TOOTH 16	MIDDLE 2	1.12	0.89	1.12	0.98
TOOTH 16	MIDDLE 3	1.02	0.77	1	0.88
TOOTH 16	MIDDLE 4	0.93	0.75	0.85	0.72
TOOTH 16	APICAL 1	0.75	0.6	0.75	0.61
TOOTH 16	APICAL 2	0.65	0.52	0.67	0.46
TOOTH 16	APICAL 3	0.4	0.29	0.45	0.35

AlphaKite Data (first set)

		X1	**X2**	**Y1**	**Y2**
TOOTH3	CORONAL 1	1.76	1.6	1.27	0.98
TOOTH3	CORONAL 2	1.43	1.44	1.17	0.93
TOOTH3	CORONAL 3	1.24	1.25	1.08	0.76
TOOTH3	MIDDLE 1	1.14	1.17	1.02	0.86
TOOTH3	MIDDLE 2	1.1	0.99	0.92	0.79
TOOTH3	MIDDLE 3	0.98	0.88	0.89	0.81
TOOTH3	MIDDLE 4	0.9	0.79	0.79	0.77
TOOTH3	APICAL 1	0.76	0.67	0.9	0.83
TOOTH3	APICAL 2	0.67	0.52	0.9	0.79
TOOTH3	APICAL 3	0.53	0.29	0.89	0.71
TOOTH 5	CORONAL 1	1.82	0.51	0.82	0.19
TOOTH 5	CORONAL 2	1.52	0.41	1.09	0.27
TOOTH 5	CORONAL 3	1.34	0.78	1.19	0.92
TOOTH 5	MIDDLE 1	1.28	1.1	1.18	0.8
TOOTH 5	MIDDLE 2	1.14	1.04	0.99	0.81
TOOTH 5	MIDDLE 3	1.02	0.93	0.92	0.89
TOOTH 5	MIDDLE 4	1.06	0.82	1.18	1.01
TOOTH 5	APICAL 1	0.94	0.76	1.04	1.07
TOOTH 5	APICAL 2	0.94	0.7	0.98	0.81
TOOTH 5	APICAL 3	0.8	0.7	0.6	0.4
TOOTH 9	CORONAL 1	1.47	1.41	1.37	0.96
TOOTH 9	CORONAL 2	1.32	1.31	1.16	0.94
TOOTH 9	CORONAL 3	1.25	1.16	1.12	1.03
TOOTH 9	MIDDLE 1	1.18	1.07	0.9	0.9

TOOTH 9	MIDDLE 2	0.96	0.93	0.98	0.96
TOOTH 9	MIDDLE 3	0.79	0.79	0.85	0.82
TOOTH 9	MIDDLE 4	0.79	0.67	0.82	0.72
TOOTH 9	APICAL 1	0.56	0.44	0.72	0.76
TOOTH 9	APICAL 2	0.29	0.26	0.58	0.49
TOOTH 9	APICAL 3	0.3	0.15	0.32	0.15
TOOTH 2	CORONAL 1	1.6	1.27	1.13	1
TOOTH 2	CORONAL 2	1.37	1.26	1.15	1.02
TOOTH 2	CORONAL 3	1.29	1.15	1.03	0.9
TOOTH 2	MIDDLE 1	1.15	0.9	0.99	0.86
TOOTH 2	MIDDLE 2	1.03	0.87	0.93	0.86
TOOTH 2	MIDDLE 3	0.92	0.78	0.96	0.8
TOOTH 2	MIDDLE 4	0.7	0.48	0.67	0.51
TOOTH 2	APICAL 1	0.63	0.08	0.56	0.11
TOOTH 2	APICAL 2	0.33	0.07	0.36	0.04
TOOTH 2	APICAL 3	0.07	0.03	0.07	0.07
TOOTH 13	CORONAL 1	1.56	1.32	1.24	1.1
TOOTH 13	CORONAL 2	1.52	1.3	1.36	1.19
TOOTH 13	CORONAL 3	1.6	1.41	1.25	1.15
TOOTH 13	MIDDLE 1	1.66	1.46	1.28	1.19
TOOTH 13	MIDDLE 2	1.51	1.4	1.24	1.12
TOOTH 13	MIDDLE 3	1.3	1.26	1.16	1.08
TOOTH 13	MIDDLE 4	1.16	1.08	1.05	1
TOOTH 13	APICAL 1	1.01	0.95	0.98	0.89
TOOTH 13	APICAL 2	0.88	0.75	0.83	0.8
TOOTH 13	APICAL 3	0.39	0.46	0.79	0.8
TOOTH 15	CORONAL 1	1.37	1.34	0.87	0.52
TOOTH 15	CORONAL 2	1.35	1.24	0.9	0.46
TOOTH 15	CORONAL 3	1.38	1.2	0.8	0.4
TOOTH 15	MIDDLE 1	1.25	1.14	0.93	0.55
TOOTH 15	MIDDLE 2	1.28	1.08	1	0.76
TOOTH 15	MIDDLE 3	1.23	1.02	1.03	0.99
TOOTH 15	MIDDLE 4	1.13	0.91	1.04	1.05
TOOTH 15	APICAL 1	1.12	0.82	1.02	1
TOOTH 15	APICAL 2	0.86	0.78	0.94	0.83
TOOTH 15	APICAL 3	0.61	0.61	0.62	0.58
TOOTH 19	CORONAL 1	1.78	1.72	1.47	1.36
TOOTH 19	CORONAL 2	1.56	1.62	1.23	0.98
TOOTH 19	CORONAL 3	1.46	1.46	1.1	0.73
TOOTH 19	MIDDLE 1	1.38	1.38	1.06	0.7

TOOTH 19	MIDDLE 2	1.29	1.22	1.09	0.76
TOOTH 19	MIDDLE 3	1.24	1.12	1.15	0.97
TOOTH 19	MIDDLE 4	1.05	1.07	1.16	1.01
TOOTH 19	APICAL 1	0.94	0.95	1.11	1.05
TOOTH 19	APICAL 2	0.86	0.83	0.94	0.92
TOOTH 19	APICAL 3	0.89	0.71	0.7	0.75
TOOTH 17	CORONAL 1	1.7	1.42	1.78	1.6
TOOTH 17	CORONAL 2	1.54	1.39	1.1	0.89
TOOTH 17	CORONAL 3	1.42	1.39	0.96	0.65
TOOTH 17	MIDDLE 1	1.4	1.37	0.95	0.58
TOOTH 17	MIDDLE 2	1.24	1.24	0.81	0.62
TOOTH 17	MIDDLE 3	1.19	1.18	0.94	0.76
TOOTH 17	MIDDLE 4	1.17	1.06	0.93	0.8
TOOTH 17	APICAL 1	1.09	0.93	1.09	0.83
TOOTH 17	APICAL 2	0.93	0.79	0.94	0.78
TOOTH 17	APICAL 3	0.65	0.63	0.55	0.57
TOOTH 7	CORONAL 1	2.25	2.19	1.05	0.8
TOOTH 7	CORONAL 2	1.9	1.53	1.3	1.29
TOOTH 7	CORONAL 3	1.71	1.69	1.36	1.19
TOOTH 7	MIDDLE 1	1.53	1.48	1.01	1.17
TOOTH 7	MIDDLE 2	1.31	1.25	1.03	0.81
TOOTH 7	MIDDLE 3	1.15	1.05	0.96	0.85
TOOTH 7	MIDDLE 4	0.93	1.07	1.32	1.19
TOOTH 7	APICAL 1	1.05	1.07	1.22	1.19
TOOTH 7	APICAL 2	1.21	1.05	1.22	1.14
TOOTH 7	APICAL 3	0.5	0.42	0.5	0.49

AlphaKite Data (second set)

		X1	**X2**	**Y1**	**Y2**
TOOTH3	CORONAL 1	1.76	1.62	1.25	1
TOOTH3	CORONAL 2	1.45	1.41	1.16	0.92
TOOTH3	CORONAL 3	1.24	1.25	1.08	0.79
TOOTH3	MIDDLE 1	1.12	1.13	1.04	0.86
TOOTH3	MIDDLE 2	1.08	1	0.92	0.8
TOOTH3	MIDDLE 3	1	0.88	0.86	0.82
TOOTH3	MIDDLE 4	0.89	0.8	0.78	0.8
TOOTH3	APICAL 1	0.79	0.68	0.9	0.83
TOOTH3	APICAL 2	0.69	0.53	0.86	0.81
TOOTH3	APICAL 3	0.54	0.31	0.88	0.74

TOOTH 5	CORONAL 1	1.77	0.53	0.81	0.17
TOOTH 5	CORONAL 2	1.48	0.4	1.12	0.28
TOOTH 5	CORONAL 3	1.34	0.78	1.2	0.9
TOOTH 5	MIDDLE 1	1.28	1.08	1.2	0.77
TOOTH 5	MIDDLE 2	1.18	1.04	0.95	0.81
TOOTH 5	MIDDLE 3	1	0.92	0.92	0.91
TOOTH 5	MIDDLE 4	1.05	0.83	1.17	0.98
TOOTH 5	APICAL 1	0.94	0.74	1.03	1.07
TOOTH 5	APICAL 2	0.93	0.7	0.97	0.8
TOOTH 5	APICAL 3	0.77	0.71	0.6	0.4
TOOTH 9	CORONAL 1	1.45	1.41	1.31	0.93
TOOTH 9	CORONAL 2	1.34	1.32	1.14	0.92
TOOTH 9	CORONAL 3	1.27	1.13	1.13	1.04
TOOTH 9	MIDDLE 1	1.18	1.07	0.9	1.1
TOOTH 9	MIDDLE 2	0.97	0.94	0.75	0.95
TOOTH 9	MIDDLE 3	0.79	0.78	0.85	0.82
TOOTH 9	MIDDLE 4	0.78	0.66	0.82	0.82
TOOTH 9	APICAL 1	0.56	0.43	0.7	0.76
TOOTH 9	APICAL 2	0.3	0.26	0.54	0.48
TOOTH 9	APICAL 3	0.3	0.15	0.32	0.15
TOOTH 2	CORONAL 1	1.59	1.27	1.11	0.98
TOOTH 2	CORONAL 2	1.43	1.27	1.15	1
TOOTH 2	CORONAL 3	1.29	1.19	1.02	0.9
TOOTH 2	MIDDLE 1	1.16	0.91	0.98	0.87
TOOTH 2	MIDDLE 2	1.05	0.87	1.01	0.85
TOOTH 2	MIDDLE 3	0.92	0.79	0.97	0.79
TOOTH 2	MIDDLE 4	0.69	0.54	0.67	0.5
TOOTH 2	APICAL 1	0.6	0.08	0.56	0.08
TOOTH 2	APICAL 2	0.34	0.06	0.35	0.07
TOOTH 2	APICAL 3	0.06	0.03	0.06	0.08
TOOTH 13	CORONAL 1	1.52	1.33	1.26	1.11
TOOTH 13	CORONAL 2	1.46	1.3	1.35	1.18
TOOTH 13	CORONAL 3	1.58	1.39	1.25	1.15
TOOTH 13	MIDDLE 1	1.66	1.46	1.29	1.18
TOOTH 13	MIDDLE 2	1.51	1.38	1.23	1.13
TOOTH 13	MIDDLE 3	1.31	1.26	1.17	1.08
TOOTH 13	MIDDLE 4	1.15	1.08	1.05	1.01
TOOTH 13	APICAL 1	1.04	0.92	0.98	0.87
TOOTH 13	APICAL 2	0.86	0.75	0.84	0.81
TOOTH 13	APICAL 3	0.4	0.47	0.76	0.79

TOOTH 15	CORONAL 1	1.38	1.34	0.87	0.49
TOOTH 15	CORONAL 2	1.38	1.24	0.9	0.47
TOOTH 15	CORONAL 3	1.35	1.21	0.8	0.4
TOOTH 15	MIDDLE 1	1.23	1.13	0.95	0.58
TOOTH 15	MIDDLE 2	1.26	1.11	0.97	0.76
TOOTH 15	MIDDLE 3	1.24	1.02	1.04	0.97
TOOTH 15	MIDDLE 4	1.13	0.94	1.03	1.06
TOOTH 15	APICAL 1	1.09	0.83	1	0.96
TOOTH 15	APICAL 2	0.88	0.79	0.97	0.83
TOOTH 15	APICAL 3	0.61	0.56	0.62	0.59
TOOTH 19	CORONAL 1	1.77	1.74	1.52	1.35
TOOTH 19	CORONAL 2	1.58	1.63	1.17	0.99
TOOTH 19	CORONAL 3	1.45	1.48	1.07	0.75
TOOTH 19	MIDDLE 1	1.37	1.36	1.03	0.71
TOOTH 19	MIDDLE 2	1.32	1.22	1.06	0.76
TOOTH 19	MIDDLE 3	1.22	1.14	1.1	0.94
TOOTH 19	MIDDLE 4	1.07	1.07	1.12	1.02
TOOTH 19	APICAL 1	0.97	0.95	1.09	1.09
TOOTH 19	APICAL 2	0.87	0.84	0.93	0.91
TOOTH 19	APICAL 3	0.88	0.72	0.68	0.76
TOOTH 17	CORONAL 1	1.72	1.43	1.81	1.61
TOOTH 17	CORONAL 2	1.53	1.4	1.11	0.88
TOOTH 17	CORONAL 3	1.4	1.38	0.93	0.65
TOOTH 17	MIDDLE 1	1.42	1.33	0.9	0.54
TOOTH 17	MIDDLE 2	1.24	1.24	0.83	0.58
TOOTH 17	MIDDLE 3	1.19	1.18	0.91	0.77
TOOTH 17	MIDDLE 4	1.12	1.05	0.94	0.8
TOOTH 17	APICAL 1	1.04	0.92	1.05	0.81
TOOTH 17	APICAL 2	0.95	0.81	0.94	0.76
TOOTH 17	APICAL 3	0.66	0.61	0.55	0.59
TOOTH 7	CORONAL 1	2.25	2.25	1.04	0.78
TOOTH 7	CORONAL 2	1.9	2.03	1.2	1.31
TOOTH 7	CORONAL 3	1.71	1.71	1.4	1.17
TOOTH 7	MIDDLE 1	1.51	1.47	0.97	1.15
TOOTH 7	MIDDLE 2	1.31	1.2	1.05	0.86
TOOTH 7	MIDDLE 3	1.17	1.05	0.95	0.83
TOOTH 7	MIDDLE 4	0.94	1.07	1.31	1.18
TOOTH 7	APICAL 1	1.07	1.09	1.22	1.19
TOOTH 7	APICAL 2	1.16	1.04	0.79	1.15
TOOTH 7	APICAL 3	0.48	0.71	0.51	0.68