

# The Use of CBCT as an Aid to Endodontic Assessment of Calcified Canals

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## Abstract

**Introduction:** endodontic treatment requires access to the pulp canal by removal of coronal dentine above this space. Calcification of the pulpal space can result from the deposition of secondary dentine which occurs throughout life or tertiary dentine in response to caries, toothwear or trauma. This increases the difficulty of endodontic treatment. The use of 3-dimensional radiographic techniques such as CBCT are being increasingly adopted for endodontic treatment planning. The role of such imaging in the management of endodontically involved calcified teeth remains unclear especially in terms of the sensitivity and specificity of canal detection. The presence of restorative materials may influence the detection rate by the introduction of artefacts into the image but there is little evidence in the literature as to the extent of these effects. Finally, there is growing interest in integration of CBCT imaging with data from intraoral scanning that could potentially be used to fabricate guides that reduce the amount of dentine removed during access of calcified teeth and improve the efficiency of the treatment.

**Literature review.** The literature was reviewed in relation to the physiology of secondary and tertiary dentine deposition and the aetiology of severely calcified or obliterated pulp spaces. Papers suggesting treatment strategies for severely calcified teeth are discussed and studies investigating the benefit of preserving the maximum amount of dentine during endodontic access were summarized. Finally, studies investigating the use of CBCT in canal detection and the integration of these images with other technologies to produce guided access were reviewed.

**Aims.** The aims of this thesis were to develop a soft and hard tissue phantom to provide sufficient clinical realism; to determine the root canal dimension of extensively sclerosed teeth using micro CT; to investigate the ability of CBCT in detecting root canal anatomy in sclerosed teeth compared with PA.

## *Abstract*

**Methodology:** The first study involved testing several materials and a radiographic phantom was produced from a real mandible and polyurethane. This was then validated as a viable soft tissue analogue of to conduct the subsequent CBCT study. A second study in which 48 calcified lower anterior teeth were selected from a tissue bank and scanned with  $\mu$ CT at 20  $\mu$ m resolution, reconstructed and imported to Mimics software allow morphometric analysis of the canal dimensions and configuration. A final study combined the phantom and teeth from the  $\mu$ CT study which were then used of the to obtain clinically realistic CBCT and PA images of teeth used in the  $\mu$ CT study using the Morita Accuitomo 170 scanner and DIGORA phosphor plate system. Six interpreters were then asked to identify the more coronal portion of the canal on both the CBCT and PA images.

## **Results:**

Analysis of the phantom in a conventional CT machine showed Hounsfield values for the soft tissue analogue that were equivalent to soft tissue.

$\mu$ CT results shows canals were almost always present at the level of the CEJ and fairly centred within the root. Canal diameter was highly variable but the average diameter at the most coronal point was 173  $\mu$ m (SD = 157  $\mu$ m). The most common canal configuration was Vertucci class I (n=17) followed by class III (n=11).

Observers identified canals from the incisal edge to the first observed pulp space at a mean distance of 10.15 mm (SD = 3.94) in the PA group and 6.79 mm (SD = 2.38) in the CBCT. This was a mean difference of 3.36 mm between PA and CBCT groups (95% CI = 1.71, 5.02) and was statistically significant ( $p < 0.001$ , paired t-test)

## **Conclusions**

Polyurethane can be used as an acceptable soft tissue substitute in the construction of a radiographic imaging phantom.

Calcified canals exhibit varying lumen diameters but do not tend to regress far from the CEJ.

Observers using CBCT consistently identify calcified canals at a more coronal position when compared to phosphor plate digital radiography.

*Abstract*

**Application:** Improvement in the knowledge of the microanatomy of calcified canals CBCT and calcified canals will aid in the treatment of these case and aid in the development of reliable and practical methods that improve technical and healing outcomes. Within the limitations of the study it would appear that CBCT is able to locate canal at a more coronal position than PA radiography.



## Chapter 1 - Introduction and Rationale

Diseases of the pulpal and peri-radicular tissues are caused by bacterial invasion of the root canal space and the subsequent spread of bacteria and bacterial by-products apically and laterally into the peri-radicular tissues invoking inflammation, abscess formation and occasionally the development of a radicular cyst (Graunaite et al., 2012, Nair, 2006, Nair et al., 2008). Endodontic infections are a source of pain and swelling and may ultimately lead to tooth loss. Furthermore longstanding chronic infections may reduce the quality of the surrounding bone making subsequent replacement with Osseo integrated implants more difficult (Saunders, 2014). The host immune system is unable to access this area and therefore unable to eradicate the infection (Nair, 2006). Thus, eradication of the infection requires endodontic treatment (root canal therapy) or the tooth to be extracted. Retention of teeth has been shown to improve the quality of life of patients. When comparing retention of teeth or replacement with osseointegrated implants patients have been shown to exhibit a clear preference for retaining the natural dentition whenever possible (Gatten et al., 2011).

### *Aims of endodontic treatment*

The aims of endodontic treatment are to disinfect the root canal and to maintain this disinfection over time. If these aims are met then peri radicular healing is expected to occur (Nair, 2006). Optimal disinfection of the root canal space requires that access to this space is gained, by removing dentine coronal to the pulp chamber or root canal space. This then allows the root canals to be identified and subsequently enlarged enough to facilitate the flow of disinfectant irrigants as far as possible into the root canal system. The combination of dentine removal and irrigation of the root canal space with sodium hypochlorite leads to a significant reduction in the bacterial load (Byström and Sundqvist, 1981, 1983). The primary aim is therefore to reduce the number of bacteria to below the threshold that initiates and sustains periapical inflammation. This disinfection is maintained by entombing any

remaining bacteria within the root canal space by the use of a well-adapted root canal filling of endodontic sealer and gutta-percha (Ray and Trope, 1995).

Endodontic treatment must also work in conjunction with the restorative or prosthodontic objectives of returning the tooth to function and to ensure that the tooth is able to withstand the biomechanical forces placed upon it during normal masticatory loading. Endodontic treatment should therefore aim to conserve as much coronal tissue as possible whilst still meeting the aims of disinfection. In addition, for teeth in the aesthetic zone, teeth must be restored in harmony with the surrounding dentition to restore the natural appearance of the tooth.

Recent interest has been placed upon more conservative endodontic access designs that, whilst still achieving the endodontic objectives of adequate chemo-mechanical cleaning, preserve as much coronal and radicular tooth tissue as possible. The rationale is that greater preservation of dentine results in higher fracture resistance of the tooth which in turn improves the prosthodontic prognosis (Gutmann, 1992).

### *Difficulty of endodontic treatment*

Endodontic access is a skilled procedure that, to perform proficiently, requires considerable experience and knowledge of anatomy along with the ability to integrate information obtained from clinical and radiographic examination (Patel et al., 2007). Endodontic difficulty of a particular tooth may be categorized using a number of different difficult assessment tools. A widely known assessment tool is the AAE Endodontic Case Difficulty Assessment Form which considers the position of the tooth in the patient factors, tooth factors and more general dental factors (AAE, 2005).

### *Calcification as an influencing factor in endodontic difficulty*

Teeth with pulp chambers and canals of reduced size are classified as moderate difficulty in the AAE classification whereas teeth with indistinct canal paths or invisible canals are classed as high difficulty.

Reduction in the size of the pulp chamber and root canals can occur due to a number of factors. Secondary dentine is deposited throughout life and subsequently many older patients demonstrate reduce pulp canal spaces. The process of additional dentine deposition may occur when the odontoblasts are subject to noxious stimuli or trauma. This results in the production of tertiary (reactionary or reparative) dentine. When the canal ceases to be visible on the radiograph this is referred to as pulp canal obliteration (PCO) or sometimes calcific metamorphosis (CM) (Malhotra, and Mala, 2013).

Calcified or sclerotic teeth are difficult to treat endodontically. Calcification of the root canal space proceeds in a coronal-apical direction and therefore the necessary penetration depth of the bur increases with increased severity of calcification. Consequently, the accuracy of this cut is diminished as a similar angulation error at a deep cut will result in a large discrepancy than a shallow cut. This is compounded by the narrowing of the lumen of the canal apically and due to the calcification process and the narrowing diameter of the root, the possibility of iatrogenic perforation increase significantly as the clinician continues to cut in an apical direction.

### *Radiography in planning endodontic access*

Traditionally standard intra oral periapical radiographs provide information regarding the root canal location and anatomy. PAs provide a 2D image of a 3D object and therefore information regarding the spatial location of the root canal system in the bucco-lingual plane is limited. In teeth with extensive calcification intra oral periapical views can have limited value as the route to the canal cannot be planned if it is not visible. Canals may become more visible in the apical region of the root but translating this information into the proper orientation is extremely difficult. As the depth of a cut increases the angle range that will safely guide the tip of the bur to the pulp decreases. That is, the margin for error is smaller when searching for a smaller pulp space that is more apical located.

CBCT has allowed a far greater amount of information to be gained before the start of root canal treatment. Much of the surrounding literature discussed the ability of CBCT to detect apical pathology with greater sensitivity and specificity than conventional radiographs (Patel et al., 2007). Less research has been conducted on the identification of root canal systems and a paucity of literature is available specifically regarding calcified teeth. CBCT has suggested as an aid to planning endodontic access in calcified cases (Lima et al., 2014) but this still requires the clinician to translate and orientate the information from the image to the clinical situation.

### *Implant surgery guides and endodontic analogues*

CBCT has been used in implant dentistry as a planning tool, allowing the correct size and length of implant to be selected before surgery (Worthington et al., 2010). This information can also be used to create surgical guides which allow the correct angulation and orientation of implant drills during osteotomy procedures. Recently CAD/CAM and CBCT technology has been integrated to improve the planning even further, allowing surgical guides to be milled at the chairside. The precision of these guides is claimed to have an accuracy of between 0.17 and 1.3 mm (Ritter et al., 2014).

The idea of guided endodontic access has been investigated to reduce the margins of error in difficult cases such as dens invaginatus (Zubizarreta Macho et al., 2015), severely dilacerated teeth (Byun et al., 2015) and simulated calcified teeth (Buchgreitz et al., 2015, Zehender et al, 2015, Connert et al 2017). Whilst guided access has been demonstrated to reduce procedural errors (Connert et al, 2017) the drawbacks are the increased level of complexity and associated cost implications.

The more complex the planning and preparation the more time consuming and costly the procedure becomes. Therefore, complex methods of accessing canals must be justified. The question of whether CBCT scans of calcified teeth are sensitive enough to aid in planning access to them has not been fully elucidated and if this is shown to be the case are CBCT scans alone enough to significantly reduce the amount of dentine removal and the number of iatrogenic perforations during endodontic access of calcified canals.

To determine the clinical benefit of CBCT in the treatment of calcified teeth the limitation of CBCT in discrimination of calcified canals must be first be determined in vitro against the gold standards of  $\mu$ CT and histological sectioning.

## Chapter 2 - Literature review

### *Dentine deposition in primary and permanent teeth*

#### Biology of dentine formation

Dentine can be classified as primary, secondary or tertiary (Kuttler, 1959). Primary dentine is deposited during the initial development of the tooth up until root formation is complete.

When the tooth is exposed to insult further deposition of dentine occurs, this is known as tertiary dentine, this can be further classified as reactionary dentine or reparative dentine. Reactionary dentine is dentine laid down in response to injury by the same odontoblasts whereas reparative dentine is produced by newly differentiated odontoblasts after the proceeding odontoblasts have been lost. This repair system is known to be activated by the release of growth factors within the dentine such as transforming growth factor- $\beta$  (TGF- $\beta$ ) and bone morphogenic protein (BMP) (Neves and Sharpe, 2018). Deposition of tertiary dentine maybe induced by a number of causes: caries, toothwear, hard tissue trauma, pulpal exposure during restorative procedures.

Further deposition of dentine within the pulp canal space after formation is a normal physiological process and approximately 0.5um of dentine is deposited daily after eruption of the tooth. This dentine is known as secondary dentine and occurs throughout life (Murray et al., 2002).

Pulp canal obliteration is a phenomenon characterised by extensive and often rapid deposition of hard tissue which is typically seen in cases with a history of trauma. It is unclear if this process is similar to that seen in reparative dentine formation or if it should be considered a distinct pathological process.

#### Effects of age

Given that secondary dentine is deposited throughout life, many older patients demonstrate reduced pulp canal spaces. There is significant inter study variation on the amount of dentine deposited each year. A study by Murray et al (2002) concluded that approximately 10 $\mu$ m of dentine is deposited on

each dentinal wall per year. (Murray et al., 2002). Furthermore, this deposition is not linear with the greatest rate of deposition occurring within the age groups of 10-30 and 31-50.

Pulp stones whilst physiologically distinct from processes such as PCO can also result in significant deposition of dentine within the root canal space. Pulp stones can manifest as true, false and diffuse types and can either be adherent, embedded or free. True stones are composed of dentine whilst false stones are the mineralized cells of a degenerating pulp. The aetiology of such stones is somewhat unclear (Goga et al., 2008) but their presence can increase the complexity of endodontic treatment significantly.

#### Effects of toothwear

The process of additional dentine deposition may occur when the odontoblasts are subject to normal physiological attrition and pathological or parafunction habits such as bruxism (Philippas, 1961). This process may explain the low level of apical pathology seen in attrition cases, even those exhibiting severe wear (El Wazani et al., 2012, Rees et al., 2011).

#### Effects of trauma

The incidence of dental trauma has been calculated to be 1.7 – 4 case/100 children/15 months with a prevalence of 6 -34% in high school children (Bastone et al., 2000, Petersen et al., 2005, Clarkson et al., 1973). A study of study of 881 servicemen showed an incidence of 3.86% (Holcomb and Gregory, 1967).

Trauma to the teeth may be sustained primarily to the periodontal ligament in the form of concussion, subluxation, lateral /intrusive luxation or avulsion or to the dental hard tissues in the form of fractures. In reality a combination of both these occur and the nature and extent of the injury influences the endodontic sequelae. Pulpal complications after trauma include necrosis, resorption and calcification or obliteration.

## *Pulp canal obliteration/calcification*

### Aetiology and epidemiology

Pulp canal obliteration (PCO) also known as calcific metamorphosis or pulp canal calcification is the diagnosed when the lumen of the canal is invisible on a peri-apical radiograph, although histologically a canal is almost always present (Kuyk and Walton, 1990). PCO is a relatively common complication following dental trauma with a frequency of 3 -24% depending on the nature of the injury and the stage of root development at the time of trauma (Andreasen et al., 1987, Holcomb and Gregory, 1967, Oginni and Adekoya-Sofowora, 2007). The frequency of PCO is most common in mild to moderate trauma; the rationale being that more severely traumatized teeth, such as those sustain fractures, will undergo necrosis before additional dentine deposition can occur.

### Teeth predominately affected

Several review articles posit that anterior teeth are most affected by PCO but the primary reference sources have either only studied anterior teeth (Holcomb and Gregory, 1967, Oginni and Adekoya-Sofowora, 2007) or the actual distribution of teeth are not stated (Oginni et al., 2009). It is therefore unclear whether anterior teeth are truly more likely to develop this condition or if this is simply reporting bias. However, given that anterior teeth are more likely to be subject to trauma (Bastone et al., 2000) and that PCO is correlated with trauma it seem likely that this assumption is correct.

### Pathogenesis of PCO

The exact pathogenesis of PCO is unclear (Malhotra and Mala, 2013) but the calcific changes within the pulp lumen are characterized by the production and deposition of an bone like or osteoid tissue. The source of this tissue has been reasoned to be either from the odontoblasts themselves or pulpal cells that differential in response to the traumatic injury (Lundberg and Cvek, 1980).

Histologically, three types of calcific tissue can be observed: dentine like, bone like or fibrotic (Lundberg and Cvek, 1980). The calcified material may have an amorphous quality and is arranged in concentric layer structure. (Piattelli and Trisi, 1993) This tissue may be entirely disconnected from



the radicular dentine or may show some intermittent connection with it (Holan, 1998). No evidence of an inflammatory process has been demonstrated in any histological analysis of calcified or obliterated canals obviating the need for de facto endodontic treatment in these cases.

A number of hypotheses have been put forward to explain the rapid calcification process observed after trauma. De Cleen (2000) argued that obliteration is a response to restriction of neurovascular supply whilst Heithersay (1975) has argued that reduction of capillary flow causes failure of the self limiting pyrophosphatase enzyme leading to the mineralisation process. Andreasen (1989) reasoned that parasympathetic inhibition from the trauma will lead to vessel narrowing and thereby reduces pulpal blood supply which in turn leads to cellular respiratory depression causing pathological mineralisation from odontoblast as a reactionary process. In immature teeth it has also been suggested that deposition of hard tissue may occur as a result of internal replacement resorption or that internal hard tissue may form a union with alveolar bone (Chen et al, 2012)

Endodontic complications can occur in teeth with significant sclerosis as a secondary complication, presumably as a result of compromised vascular flow. The incidence of pulpal necrosis has been given as 8.5% (Robertson et al., 1996) and this incidence has been shown to increase over time (Oginni and Adekoya-Sofowora, 2007). Since a lumen has been shown to be always present, albeit greatly reduced, (Kuyk and Walton, 1990) there is the potential for bacteria to progress apical. Teeth with partial radiographic obliteration are more likely to develop symptoms than teeth with total obliteration (Oginni and Adekoya-Sofowora, 2007).

A study by Oginni et al (Oginni et al., 2009) has shown 33% of teeth with PCO develop PA lesions indicated that endodontic treatment of these teeth is often required more often than previously thought.

### *Treatment of severely calcified teeth*

Infection of the root canal space requires endodontic treatment to eradicate it. This involves locating and subsequent enlargement of the root canals to facilitate irrigation and disinfection. PCO teeth are

difficult to treat endodontically. Calcification of the root canal space proceeds in a coronal-apical direction and therefore the necessary penetration depth of the bur increases with increased severity of calcification. Consequently, the accuracy of this cut is diminished as a similar angulation error at a deep cut will result in a large discrepancy than a shallow cut. Compounded by the narrowing of the lumen of the canal apically and due to the calcification process and the narrowing diameter of the root, the possibility of iatrogenic perforation increases significantly as the clinician continues to cut in an apical direction.

### Access

Clinical articles discussing the appropriate access of PCO/calcified root canals are composed entirely of case reports or series of case reports(De Cleen, 2002, Amir et al., 2001, Tavares et al., 2012) The clinical techniques discussed include the differentiation of the different colour and opacity of secondary and tertiary dentine (Krasner and Rankow, 2004), the use of small or stiffer 'pathfinder' files to locate and penetrate into the potentially irregular lumen (Amir et al., 2001, Malhotra and Mala, 2013), the use of magnification (Selden, 1989) or, anterior teeth, access through the incisal edge(McCabe, 2006). Even with knowledge of pulpal and root anatomy, such 'blind' cutting increases the risk of perforation. Therefore, the use of check radiographs to assess the course of access is often recommended (Ngeow and Thong, 1998).

A frequent occurrence that is noticeable in these articles is that the post-operative radiographs often reveal very large access cavities. Whist there is little supporting evidence for fracture resistance when preparing conservative access cavities over traditional ones in anterior teeth (Krishan et al., 2014), it would seem logical that excessive removal of tooth structure would almost certainly result in a clinically significant weakening of the tooth (Ng et al., 2006). In addition such cases require significant amounts of time to locate canal systems and as calcified canals are much smaller and difficult to locate this leads to the removal of extensive amounts of dentine (McCabe and Dummer, 2012)

Depth, and angulation in both mesio-distal and bucco-lingual/palatal planes must be correct in order to access the pulp canal lumen. Even with calcification some of the distances to the pulp chamber can show quite small levels of variation (Deutsch and Musikant, 2004, Deutsch et al., 2005, Lee et al., 2007). However, with decreasing lumen diameter the difficulty in successfully accessing the canal is greater. Thus, a large access maybe created to locate the canal. This increases the risk of perforation which in turn leads to a lower success rate of treatment (Ng et al., 2011)

## Negotiation

An ex vivo study by Molven (Molven, 1973) on 46 extracted teeth found that there was good agreement between a previous a diagnosis of PCO and the non-penetrable nature of the canals when a standardized instrumentation technique was attempted. Microradiographs of the non-penetrable canals showed that in 75% of the canals instruments had clearly deviated from the canal lumen and penetrated into the circumpulpal dentine.

Missing anatomy leads to a reduction in successful healing outcomes (Cantatore et al., 2006). PCO makes finding the anatomy more difficult because of recession of the pulp chamber, smaller canals are more difficult to identify and may exhibit a low natural taper which is difficult to access and negotiate with, even low taper files as these exhibit binding along the length of the files, a phenomenon known as taper lock. This both impedes further advancement of the instrument as well as increasing the torsional stress upon the file increasing the change of separation of the file due to torsional stress.

It is logical to assume then, that teeth with PCO will exhibit poorer technical outcomes and consequently show lower healing outcomes (Ray and Trope, 1995, Ng et al., 2007). However, whether this occurs is not elucidated by the literature. Nevertheless, planning endodontic treatment on teeth with PCO requires careful consideration of the depth and angulation of tissue removal to avoid excessive overcutting that potentially reduces the prognosis of the tooth.

### *Arguments for conservative endodontic access*

Traditional strategies for successful endodontic access are firstly, completely de-roof the chamber and secondly, create straight-line access to the mid 1/3 of the root canal.

The rationale behind these strategies is largely due to the nature of the instruments employed at the time of their formulation. Stainless steel files are not as flexible as their more modern nickel titanium counterparts and consequently removing the roof of the pulp chamber and creation of straight-line access made placement of stainless steel files into the mid 1/3 of the root easier in many cases. Additionally, the argument was made that leaving an overhanging remnant of pulp chamber roof could lead to necrotic tissue being left behind which would then serve as a nutritional source to bacteria. Some authors suggested, and still suggest, that a proper access cavity would be one in which all canal orifices should be visible when viewed from the occlusal aspect

### Fracture resistance of teeth with conservative endodontic access cavities

A study by Reeh (Reeh et al., 1989) investigated the relative reduction in tooth stiffness in relation to various restorative and endodontic procedures. The results of the study concluded that endodontic access cavities account for a small proportion of tooth stiffness. From this finding it could be argued that endodontic treatment should not significantly weaken teeth.

However numerous studies have found that extraction of endodontically treated teeth is more frequent when no cuspal coverage restoration has been provided (Salehrabi and Rotstein, 2004). The argument to preserve the maximum amount of peri-cervical dentine as possible has been reintroduced by Clark and Khademi (Clark and Khademi, 2010) who have argued that many of the dogmas of endodontic access contribute to the premature loss of teeth. The article however suffers not just from a conflict of interest (the authors disclose a royalty from sales of burs specifically designed for minimal endodontic access) but also the fact that the article is almost entirely driven by the technical aspects of achieving more conservative design but with little support for this from the existing literature.

This concern was recently addressed by Krishan et al (2014) (Krishan et al., 2014) who investigated the fracture resistance of conservative endodontic cavities (CEC) against more traditional access cavities (TEC). In this study molars and premolars were found to be able to withstand higher forces before fracturing when they were accessed by a more conservative endodontic cavity design. Whilst this lends supports to conservative access within posterior teeth the study was conducted *in vitro* with initially intact teeth. This could not be argued to be an honest reflection of reality where most teeth treated endodontically are substantially damaged by caries or heavily restored. Furthermore, static loading may not be representative of normal cyclical masticatory function.

Unfortunately, no *in vivo* data to determine the benefit of minimally invasive endodontic access cavities is available. From a restorative perspective minimizing dentine removal during endodontic access would appear beneficial, as each cycle of removal and replacement leads to progressively smaller amounts of remaining tooth tissue. Thus, minimizing the initial tissue destruction may prolong the restorative prognosis of the tooth.

Given that the current evidence suggests most endodontically treated posterior teeth should be restored with an indirect restoration and that indirect restorations usually require removal of coronal tissue it is sensible to suggest that conservative preparation of both endodontic access cavity and of the indirect restoration itself should be encouraged. A study by Bandlish et al (Bandlish et al., 2006) investigated the remaining amount of tooth structure after endodontic access and preparation of the tooth for a full coverage crown. Using a tooth restorability index, they found that restorability scores varied between 2 to 13 out of a maximum possible score of 18. Whilst this attempts to objectify the co-destructive nature of a combined traditional endo-restorative treatment approach the index suffers from a lack of clarity of what the scores actually mean, an overly complex scoring system that severely weakens its potential for practical application and, most importantly, is still an unvalidated index.

## Conservative endodontic access and debridement of the root canal space

The study by Krishan et al (2014) also investigated the ability of endodontic instruments to effectively instrument the walls of the canal. They found that the apical third of the distal root of lower molars was the only area that was significantly different in terms of canal wall instrumentation. The objection that conservative access impedes debridement of the canals is therefore not supported by this study.

## *Radiography in planning endodontic access*

### Intra oral radiographs

Traditionally a standard intra oral periapical radiograph is the view of choice to provide information regarding the root canal location and anatomy. IOPAs provide a 2D image of a 3D object and therefore information regarding the spatial location of the root canal system in the bucco-lingual plane is limited. Recently CBCT has allowed a far greater amount of information to be gained before the start of access procedures (Patel et al., 2007) but still requires the clinician to translate and orientate the information from the image to the clinical situation.

Frequent problems with standard IOPA in endodontic access are elongation or foreshortening of the films which distorts the real length of the tooth. Additionally, the image is a 2D representation of 3D object and assessment in the bucco-lingual plane is impossible. Multiple images taken at different angles may allow some discrimination within this plane by using an understanding of parallax.

Other imaging modalities include bitewing radiographs which benefits from a reduction in the distortion due to mis-angulation and therefore is more accurate when estimating the depth of cut needed to access the pulp chamber. This also suffers from the lack information in the sagittal plane. Tuned aperture computed tomography (TACT) has also been suggested as a method of gaining more information in the bucco-lingual dimension (Nance et al., 2000). This imaging modality uses several IOPA taken from different angles to produce image 'slices' in a similar manner to CT or

CBCT. However, with the advent of limited field of view CBCT this method has little advantage over the later in terms of information gained.

When determining the sensitivity and specificity of periapical radiographs for identifying root canals the literature varies. A study by Neekakantan et al (Neelakantan et al., 2010b) found that when using conventional digital radiology root canals were missed in 23.8% of teeth imaged. Although it is likely that this percentage would vary depending on the type of digital sensor or plate used.

The question to what the minimum canal diameter is detectable on a conventional or digital PA is not clearly addressed in the literature. A radiographic and histological study on cadavers with teeth with severe sclerosis/calcification demonstrated that all teeth had a root canal present even when the canal appeared totally sclerosed on the radiograph. No canal in this study was found to have a diameter which was less than 100  $\mu\text{m}$  which is the tip size of #10 K file. However, the presence of calcifications or irregularities may be the reason that not all canals can be instrumented with a #10 k file or even #8 or #6. The average diameters of just visible canals are not given but as those not visible were still larger than 100  $\mu\text{m}$  it would seem that the size would be somewhat bigger than this. Interestingly the authors found that radiographic measurements were sometimes larger than those determined using sectioning. This counter intuitive finding can be explained by the shape of the canals themselves. No canals are truly circular in cross section and roots such as the mesio buccal roots of upper first molars can be elliptical or hour glass in shape. The shape/depth of the canal plays an important role in the appearance on the radiograph. (Kuyk and Walton, 1990) with canal wide in the bucco-lingual dimension being more visible.

## Factors affecting canal detection

### Spatial resolution

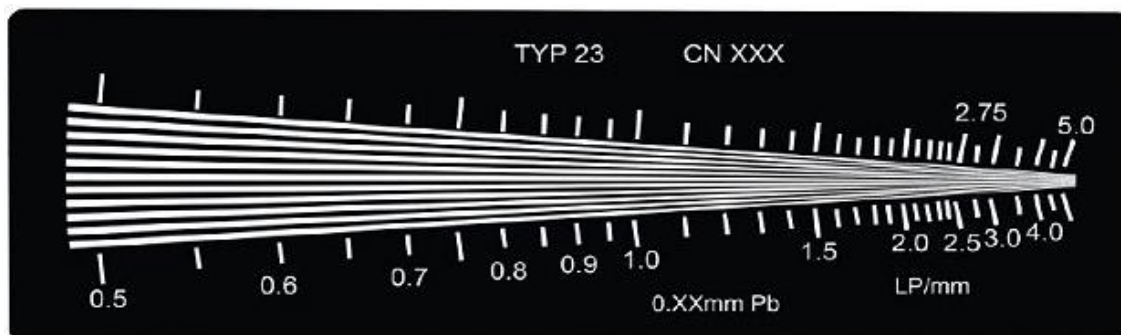


Figure 5-1. A line pair gauge demonstrating the use of converging line to assess spatial resolution.

Spatial resolution is a measure of how small a space can be perceived on the radiograph. Traditional 'wet' film has a spatial resolution of up to 20 lines per millimetre (lp/mm) due to the fine grain size of the silver halide emulsion. Digital sensors have a theoretical spatial resolution of up to 25 lp/mm but due to electronic noise the reported resolution can be 20 lp/mm or less. Phosphor plates are reported to range between 8 to 24 lp/mm. These reported ranges often come from the manufactures themselves. In a study using a quality assurance phantom, Mah et al (2011) found that the actual lp/mm was significantly lower, ranging from 8 lp/mm for phosphor plates to 8-15 for CMOS digital sensors.

### Contrast resolution

Contrast resolution is defined by the number of grey levels that can be differentiated in the image. Contrast resolution maybe more important when detecting root canals than, for example, a working length radiograph because identifying the latter involves differentiating between two materials of very different radiopacity (dentine and metal), whereas in the former the canal contents will have a grey



Figure 5-2. Left: 1 bit image with 2 grey levels, Middle: 4 bit image showing 16 grey levels, Right: 8 bit image showing 256 grey levels.



value that is closer to dentine. The interplay between spatial and contrast resolution is therefore likely to be more complex when attempting to detect root canals (Abella and Kanagasingam, 2016).

#### *Additional factors*

Anatomical noise refers to the superimposition of anatomical structures over the area of interest. The changes in radiopacity of these structures results in a reduction of contrast that may make subsequent interpretation of the image more difficult.

In addition, periapical films should be placed parallel to the long axis of the tooth to provide a dimensionally accurate image. In some instances, such as a shallow palate, this may not be possible, and the resultant image is geometrically distorted in the long axis (White and Pharoah, 2014).

#### *Perception*

Although the *physical* characteristic of radiography can be calculated and, in some cases, measured. The interpretation of any image by an observer is *psychological* process. A number of factors including observer experience in both interpretation of radiographic images and also the proposed clinical procedure itself will influence the perception of the image. In addition to the observer, the environment in which the observer views in images is also critical.

Many radiologists use specific monitors and view images in a darkened room to increase the ability differentiate grey values. Haak et al (2002) showed that dimming view room lights to 70 lux significantly improve the observer's ability to detected differences within the grey scale. A common recommendation is that view room lighting should be 300 lux or less to gain the most information from the image.

#### *Theoretical limits to image formation*

The Shannon-Nyquist theorem states that to detect a signal the sampling frequency must be greater than twice the frequency of the input frequency (Carter and Veale, 2013). In radiography this can be applied to the greyscale in image formation. Put simply this means that for a pixel to be registered on an image twice the number of pixels need to be sampled, thus to image a 40  $\mu\text{m}$  space, two pixels of 20  $\mu\text{m}$  must be imaged. It can therefore be seen that manufactures claims of minimal pixel or

voxel size, whilst true on a technical level, is somewhat misleading as it does not equate to the detection of structures at this size but rather the minimal detectable structure will be twice this resolution.

Conversely, an object that is smaller than the voxel or pixel size of a sensor maybe detected if the contrast of the object is sufficiently high. This occurs because attenuation of the beam is averaged over the voxel/pixel and if the contrast of the object is high enough it will effectively fill the pixel. This phenomenon is known as the partial volume effect and can make objects appear larger than they are (Harvey and Patel, 2016).

### Cone Beam Computed Tomography

Computed tomography was developed by Sir Godfrey Hounsfield during the 1960s with the advent of the first medical systems being introduced in 1971. The concept of CT is the comparison of x-ray attenuation taken at different angles through an object to produce axial 'slices'. The system utilises a method by which the linear attenuation coefficient of water is used as the reference point set at zero and air is set at -1000 Hounsfield unit (HU). These values being chosen as human (and other organisms) are comprised mainly of water. Early systems only allow viewing of images in the axial plane since the voxel was not isometric.

CBCT imaging was developed in 1994 by Attilio Tacconi, Piero Mozzo, Daniele Godi and Giordano Ronca with the first commercial scanners being made available in 1996. CBCT uses a divergent cone of X rays rather than a narrow beam as in conventional CT. the benefit of this technology is that lower radiation exposure is required and that the three-dimensional units of the image, the voxels, are isometric. This allows accurate reconstruction of the image in any plane.

CBCT in endodontics has generated huge interest with its ability to reveal greater information about the periapical status of teeth, endodontic anatomy and healing (Patel et al., 2015). CBCT scanners have evolved rapidly since their relatively recent introduction. Newer scanners have the ability to change the field of view to more restricted dimensions thereby reducing the radiation dose.

Additionally, some scanners can take 180° or 360°, the later results in a larger radiation exposure but allows reformatting of the image to remove artefacts, such as those caused by movement.

CBCT has been shown to have a high degree of sensitivity for detection of canals when compared to conventional radiography (Soares de Toubes et al., 2012, Neelakantan et al., 2010b, Neelakantan et al., 2010a). A study of 72 teeth by Matherne et al (Matherne et al., 2008) compared detection rates of root canals between digital CCD and phosphor plates with CBCT. The authors found that endodontists failed to detect a root canal in 40% of teeth when compared to CBCT. However, there is little evidence of the use of CBCT detection rates and canal diameter.

In addition to the configuration of the root canals, the surrounding structures can influence the CBCT image. Artefacts in CBCT relevant to clinical examination can be classed as either extinction artefacts; beam hardening artefacts; partial volume effect; aliasing artefacts; ring artefacts; and motion artefacts (misalignment artefacts) (Schulze et al., 2011). One of the advantages of IOPAs is that they do not suffer from such artefacts which means they are especially useful during treatment in the heavily restored dentition when a number of restorative materials present in the surrounding area have potential to produce artefacts.

Voxel size has been suggested as a possible factor in canal detection. This is a logical suggestion since smaller voxel sizes equate to higher resolution of the image and in theory this should increase the detection of fine structures such as root canals. However, voxel size may not be as important as examiner experience (Vizzotto et al., 2015). A Brazilian study investigating the diagnostic reproducibility of MB2 canals found that examiner experience was a better predictor of identifying these canals than was voxel size. The actual determination of the presence of an MB2 canal in this and (Vizzotto et al., 2013) previous study was done using a tooth clearing technique. In one study 9 of 89 teeth (10.1%) were excluded due to failure of the clearing protocol (Vizzotto et al., 2015)

#### *Use of CBCT in management of calcified canals*

A number of clinicians have advocated the use of CBCT as an adjunct to aid in the management of calcified canals. Some clinician can adopt almost a zealous approach to the use of CBCT in such cases, some even going so far to take pre-operative, intra-operative and post-operative scans (Azim, 2015). Whilst this is extreme the number of papers supporting the adjunct use of CBCT is continuing to rise.

Rocha et al (2014) described the use of CBCT as an aid to locating in the case of a calcified molar whilst Yang et al (2016) described a case series of 13 teeth (16 roots) where CBCT was used to aid treatment in molars with coronal or middle apical third calcification. However, no analysis was performed, and no control was examined as an alternative meaning that CBCT was assumed to be of benefit without offering convincing evidence of its value.

Floratos and Miltiadous (2017) describe the use of intra operative CBCT for locating canals. They describe a technique where, after a failed attempt to locate the canal, GP is compacted over an area where the canal would be expected to be located and then a CBCT scan is taken. The GP then acts as a reference point from which the distance and direction of the canal can be measured. However, their study demonstrates an issue seen in other papers that recommend intra operative imaging, namely the excessive removal of tooth tissue before using radiography.

Although not the aim of this study a question is raised over whether pre-operative scans are more useful than intra-operative scan. Presently, there is no evidence to suggest which approach is superior, but it is likely that the ability of the clinician to relate the information three dimensionally into the clinical situation will be central to the answer.

## CBCT and image quality – contributory factors

### Device factors

A number of factors can affect the radiographic image produced by CBCT. Broadly these can be divided into device, physical and perception factors.

Device factors will involve the quality of the components, namely the sensor array. As the most expensive component, cheaper units utilise lower quality or smaller sensors and this will affect the quality of the final image.

There are three types of sensor in commercial CBCT units. The first type are image intensifiers. This technology has been used in other dental radiology methods such as panoramic radiographs. A phosphorescent scintillator screen emits visible light when struck by an x-ray beam which is then detected by a photocathode and recorded by a camera. These conversion steps all allow the introduction of noise which degrades the image. The second and third type of sensor use digital panels. The first type uses a method similar to a scintillator to create light that is detected by a photodiode array whilst the latter type converts x-rays directly into an electrical signal. Whilst direct digital sensors have the best detection efficiency they are much more expensive than indirect digital panels meaning cheaper units will usually incorporate the former.

Regardless of the sensor type, sensors can degrade over time. It is therefore necessary that proper quality assurance protocols are in place to ensure that machine are producing diagnostic quality images and allow any necessary remedial work.

Once the data has been captured by the sensor it is then used to derive the image in a process called reconstruction. The most usual form of reconstruction is called filtered back projection, in which the signal received by the sensor is projected back along its path to create the image. Multiple projection is required to determine the shape of an object which are then 'filtered' to remove artefacts. Unfortunately, the filtering process can remove useful data or add artefacts itself. To overcome this problem, a process called iterative reconstruction has been developed that attempts to model the data to derive the true shape of the object. This method has the potential to produce much better images but at present requires significant amounts of computing power and time.

### **Field of view and resolution**

Most CBCT devices can image a variety of view sizes. Regardless of the view size, the image is projected over the entire sensor. Thus, smaller fields of view can achieve greater resolution due to the smaller object being projected across the entire sensory plate. This is an important consideration when requesting images for endodontic evaluation and must be made clear to the radiographer.

Resolution involves the interplay between spatial resolution, contrast resolution and noise as described earlier. CBCT has poor contrast resolution, however attempting to increase contrast by lowering the kV will increase noise and therefore a balance must be made to ensure the correct contrast to noise ratio. Spatial resolution and contrast resolution can be tested using quality assurance phantoms.

Artefacts in CBCT can come from a number of sources such as extinction artefacts, beam hardening artefacts, partial volume effect and EEGE, aliasing artefacts, ring artefacts and motion artefacts (misalignment artefacts). Additionally, noise and scatter also contribute to degradation of the image (R Schulze et al, 2011). Artefacts are in part derived from the method of 3D reconstruction of the CBCT image. All CBCT scanners currently use back projection utilising the Feldkamp algorithm as this allows fast reconstruction but consequently this technique, due to the approximations it makes, introduces artefacts into the CBCT data set.

### Previous studies on canal detection

The majority of studies on CBCT and root canal anatomy have focused on the mesiobuccal root of the maxillary first molar. There is some conflicting evidence of the advantage of CBCT over conventional periapical radiograph. Donmark et al, (2013) found no difference in detection rates between CBCT and digital radiography in detecting a second mesiobuccal canal. Conversely, Matherne et al. (2008) compared CBCT against digital radiography and phosphor plates. They found that in maxillary molars CBCT identified on average 3.58 canals whilst CCD digital sensors detected 3.1 and phosphor plates 3.0. They concluded that even experienced endodontists will miss one canal in approximately 4 of 10 teeth when using digital or phosphor plate IOPAs.

### *CBCT and CAD-CAM guides*

Computer guided access in implant surgery is well established (Ganz, 2015) (Mascarenhas et al., 2014). Further integration with digital technologies such as intra-oral scanning and 3-d printing has further simplified the work flow of producing such guides.

Implant guides can be highly accurate. Geng et al (2015) (Geng et al., 2015) found that implant surgeries using tooth supported implant guides had final implant positions with an average angular deviation of  $1.72^{\circ} \pm 1.67$  from the digitally planned implant position. Furthermore, the final implant apex position deviated from the planned position by an average of  $0.37\text{mm} \pm 0.35$ . Such level of accuracy opens the possibility of using such guides for endodontic access.

The idea of guided endodontic access has been proposed that would reduce the margins of error in difficult cases such as dens invaginatus (Zubizarreta Macho et al., 2015), severely dilacerated teeth (Byun et al., 2015) and simulated calcified teeth (Buchgreitz et al., 2015).

Buchgreitz et al (2015) described a prototype endodontic access guide using the same technique as an implant surgical guide (Buchgreitz et al., 2015), Using a modified parallel sided pilot drill access was guided by a metal sleeve within a 3d printed surgical sent. This was tested on simulated calcified or obliterated canals and showed high levels of precision with low risk of iatrogenic events such as perforation. The use of a parallel bur however is not conservative, particularly in deeper access cavities as it does not conform to the natural conical shape of the root. The problem with this type of design of guide is that a parallel drill is necessary to maintain guidance from the metal sleeve.

Zehender et al (2015) also developed a guided endodontic access protocol using modified implant guides. Again, the use of parallel burs was used creating large access cavities. Connert et al (2017a) further refined this concept with the introduction of a micro guided approach. Effectively miniaturizing the process to conserve tooth tissue by using a parallel bur 0.9 mm in diameter. The accuracy of this technique was verified using a simulated calcified lower incisor tooth (Connert et al, 2017b)

It is increasingly evident that this technology has sufficient accuracy to allow the fabrication of endodontic access guides that will reduce the incidence of iatrogenic errors, reduce clinical treatment time *and* conserve tooth structure, especially in cases of high complexity.

However, the basic anatomical data have not yet been fully elucidated, and the question remains to be answered over whether such complex treatment strategies to manage calcified canals are necessary. It may well be that, with deeper understanding of the morphometrics of canal calcification, a modified approach of the traditional access cavity will be sufficient to guide the clinician using, simpler, more economical methods to achieve the same desired technical and clinical outcomes.



## **Aims/Research Question/s**

1. Identify a material which are able to provide soft and hard tissue analogues for a radiographic phantom that will provide the necessary clinical realism for radiographic interpretation in vitro
2. Using micro CT, what are the canal dimension of extensively sclerosed teeth in terms of diameter of canals, concentricity of canals, depth of the initial start points of the canal from the incisal edge and canal configuration.
3. What are the limitations of CBCT in the identification of root canal anatomy in relation to the distance of the canal from the incisal edge and the canal diameter.
4. Is CBCT able to detect smaller canals than conventional periapical radiographs as well as detecting canals in a more coronal position?

## Chapter 3 Morphological description of calcified canals using micro computed tomography

### *Introduction*

Despite the notorious reputation calcified canals have in terms of their difficulty to treat, there is limited literature on the morphological and dimensional aspects of these teeth. Why such paucity of data exists is unclear. Perhaps the relatively low incidence of pathology on such teeth makes collection of suitable samples difficult coupled with the fact that the rapid calcification observed after trauma is predominately seen in maxillary anterior teeth which are less likely to be extracted unless absolutely necessary. Roots exhibiting apical pathology may also be subject to attempts to resolve the infection via endodontic treatment, thereby rendering them unsuitable for morphological studies regardless of whether treatment was successful or not.

### Canal diameter

Kuyk and Walton (1990) compared the radiographic appearance of root canals with the true histological dimensions in 89 sections taken from 41 roots of 36 teeth from 5 cadavers. 4 roots showed no sign of a root canal radiographically but in their study *all* sections of *all* roots demonstrated the presence of root canal. Furthermore, no canal lumen was less than 100 microns which is clinically significant since this is the size of the tip of a #10 k file. Interestingly, calcifications within the canal were observed but this did not correlate strongly with the radiographic dimensions. Severe obliteration, however, was correlated and it is possible that the relationship between detection rate and canal calcification is not linear or in other words 'obliteration' of the canal may only be observed at a critical lumen diameter.

### Canal histology

The histological studies available describe various morphological appearances of the canal.

The tissue may appear to be tubular or atubular dentine or even osteoid. Holan (1998) suggests that this appearance is a result of rapid deposition around odontoblasts, creating inclusions within the

mineralised tissue thus giving the appearance of osteoid tissue rather than the actual existence of bone.

Calcifications can arise from a number of processes. Calcifications may be either attached to the root canal wall or may be 'free' within the lumen. Pulp stones can also become embedded in the root canal wall (Goga et al, 2008). Dentine may also arise from a tertiary process. In response to irritants or injury the odontoblast may deposit reactionary dentine contiguous with the existing dentine tubular structure or in the event the odontoblast dies off, newly differentiated odontoblast forms reparative dentine that is not contiguous with the existing dentine structure. The exact mechanism of rapid dentine deposition within the pulpal space, typically observed after trauma, is not fully understood although a number of theories exist which have been discussed earlier.

### Canal concentricity.

In a study of 500 permanent teeth comprising both maxillary and mandibular anterior, premolar and molars, Krasner and Rankow (2003) developed a set of 'laws' for locating canals during access

1. Law of centrality: the floor of the pulp chamber is always located in the centre of the tooth at the level of the CEJ.
2. Law of concentricity: the walls of the pulp chamber are always concentric to the external surface of the tooth at the level of the CEJ.
3. Law of the CEJ: the CEJ is the most consistent, repeatable landmark for locating the position of the pulp chamber.

Whilst the methods Krasner and Rankow employed describe using all types of teeth the papers focused strongly on posterior teeth and mentions nothing regarding how mandibular incisors obey these laws as these teeth often exhibit two canals (Vertucci, 1984)

During the development of the tooth the root canals are of uniform thickness Krasner and Rankow, (2003). After eruption secondary dentine deposit continues in such a uniform manner (Murray et al 2002)

It has therefore been argued that in to locate the canal one should look in the centre of the tooth root as this is where the canal will be located. There are problems with this recommendation.

1. The deposition of dentine in calcified canals may result from a number of processes. In the case of secondary dentine formation, which is slow, uniform deposition can be expected but in cases of reactionary or reparative dentine formation, such uniformity may not exist. It is therefore possible that teeth that have undergone particular calcification processes may not exhibit this symmetry.
2. The root is not necessarily round and is often oval such as those seen in lower anterior teeth or maxillary premolars. Consequently, in the instance of a 'dumbbell' shaped root and if the assumption is correct that dentine wall thickness is uniform, the remaining lumen may not be located in the centre of the root. Indeed, extensive calcification in such root shapes could give rise to two root canal spaces lateral to the centre. It is likely that canal configuration plays a clinically significant role when locating canals. In these instances, it has not been shown if such canals obey Krasner and Rankow's laws, since in their study they sectioned teeth at the level of the CEJ whereas in lower incisors the canal often has a 1-2-1 configuration meaning that a single canal would have been seen at the level of the CEJ.
3. Localised or free pulp calcifications may not be evenly distributed throughout the canal space. Adherent or embedded pulp stones may create an irregular structure in which the remaining lumen is lateral to the centre of the tooth. Differentiating between different calcification processes maybe impossible clinically. Additionally, there is little histological or  $\mu$ CT evidence to indicate the relative frequency of each morphology

The aim of this study was to determine the morphology and the dimensions of teeth with canals that were difficult to visualise on a standard periapical radiograph using micro CT in order to determine the typical canals lumen size of such teeth as well as describing the concentricity of lumen and the configuration of the root canal system.

## *Methodology*

### Tooth selection

All teeth were selected from LUDH tissue bank. These were teeth that had been donated to the university by prospective students. Ethics for such collection had previously authorised by LUDH and required dentists to obtain consent from any patient who agreed to such collection of extracted teeth.

Teeth stored in the tissue bank are routinely sterilized and stored in Gigasept AF (Schülke & Mayr GmbH, Norderstedt | Germany). Some of the samples had previously been stored in thymol solution.

Teeth were selected from the bank if they were lower incisor teeth and were completely intact from crown to apex. Teeth with large carious lesions or those that were heavily restored teeth were excluded. Some teeth with minor cavities or restorations were included.

### Ethics approval

As teeth in the LUDH tissue bank were collected on the basis of educational use further ethics approval was necessary. Approval was granted by the ILT Ethics Review Group on the 10th March 2016, reference number: 201612129.

The human mandible used was a previous teaching model available at the University of Liverpool Dental School. This specimen was over 100 years old and therefore not subject to ethical approval requirement for the study.

### Screen radiographs

Several hundred lower anterior teeth were selected from the tissue bank, and radiographs were taken with the NOMAD portable X-ray system (Aribex, Inc., Charlotte, North Carolina) set at 0.2 secs using size 2 phosphor plates (DIGORA accessory intraoral imaging plates (Sorendex, Tuusula, Finland)). See table below

Radiographs were taken of the four teeth placed in a foam sponge at a distance of approximately 100mm at both 90° (bucco-lingual) and 0° (mesio-distal) to the incisal edge. Radiographs were developed using a DIGORA machine and software (Sorendex, Tuusula, Finland).

## NOMAD settings

Anode voltage	60 kV true DC
Anode current	2.3 mA
Exposure time range	0.01 – 0.99 s
Focal spot	0.4 mm
Inherent filtration	>1.5 mm Al
Source to skin distance	20 cm
X-ray field	60 mm round

Table 3-1. Settings of the NOMAD portable X-Ray system. Note that these are inherent in the unit and therefore cannot be changed.

## Selection criteria

Teeth with no obvious canal or those perceived to be severely reduced in size in the coronal 1/3 of the root were then selected from the radiographed teeth. The teeth were radiographed again, and the most calcified teeth were selected. 48 teeth were selected from the available images and then individually radiographed in a bucco-lingual and mesio-distal direction using the same radiographic settings. The sample number was selected as it was intended that these teeth would be used for a later study investigating access cavities in teeth exhibiting severe calcification.

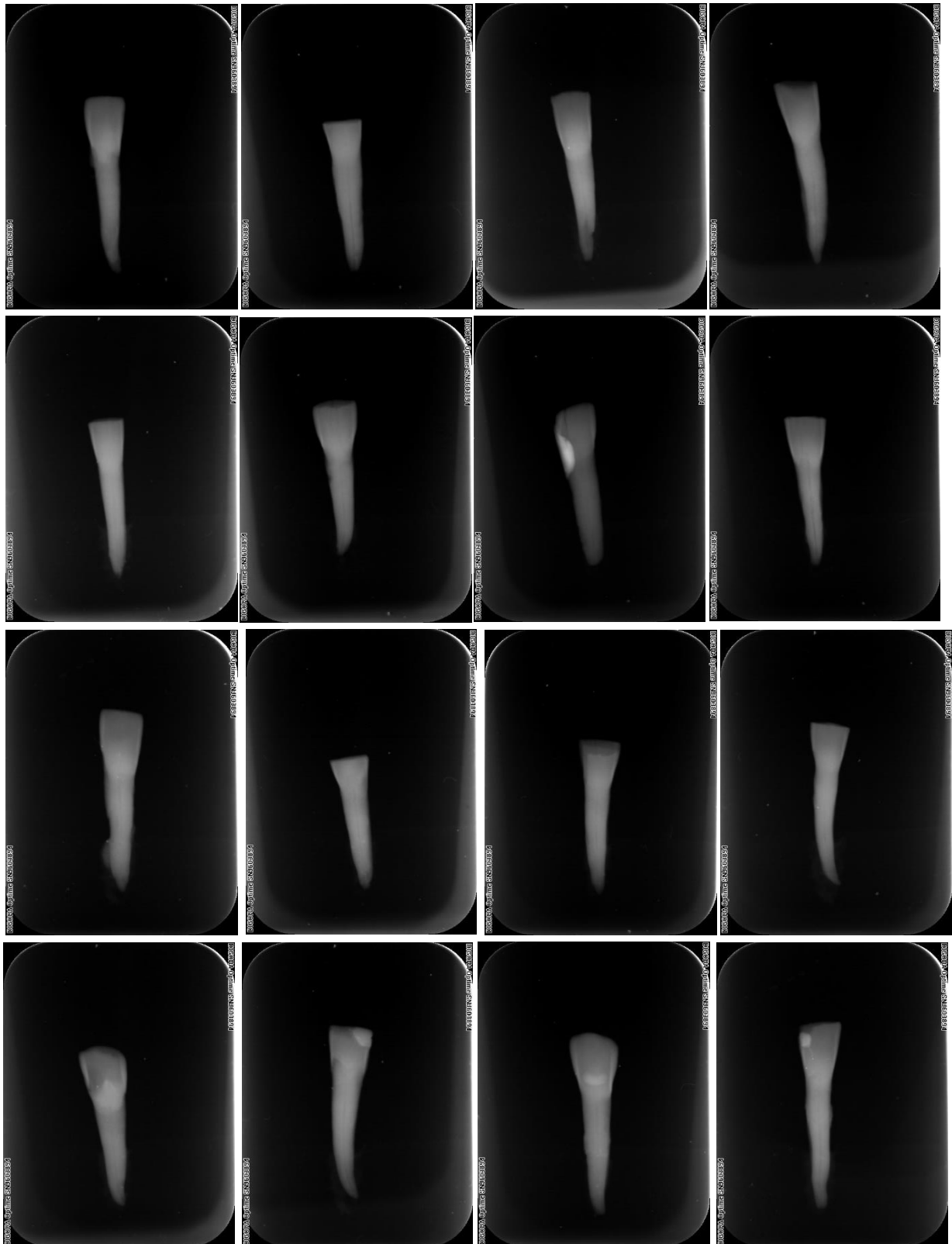
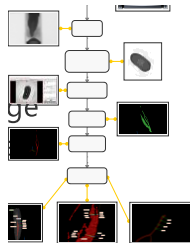


Figure 3--1. A selection of phosphor plate radiographs taken in the bucco-lingual axis. Teeth were selected if the canal was extremely reduced or invisible in the coronal one third of the root.

### μCT sample preparation

Study teeth were sorted in distilled water in cryo tubes. For μCT scanning teeth were placed in modified 10 cc syringes and fixed with soft tissue paper to keep the teeth centred within the body of the syringe. The syringes were then filled completely with distilled water and then placed within the scanner robot autoloader and the following setting selected for the machine.



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Figure 3-2. Flow chart outline the process from scanning samples to morphometric analysis.



## Scanner settings

All teeth were scanned with a Bruker SkyScan 1272 (Bruker, Kontich, Belgium) using the following settings.

- Rotation step (deg) 0.300
- Averaging (frames) 2
- Random movement: 30
- Energy filter Al 0.5mm
- Pixel size: 20 $\mu$ m
- Image format: 1344x896
- Vertical position 34.00
- Partial width: 100%
- Standard scan in central camera position
- Oversize scan: end position (mm): 52.00

## Reconstruction

Reconstruction of the images was performed using the NRecon reconstruction software (Bruker, Kontich, Belgium) supplied with the scanner using the following parameters: beam hardening reduction of 30%, ring artefact reduction of 6 and smoothing of 1.

## Analysis with Mimics

The PNG reconstructions from the  $\mu$ CT were imported in Mimic 20.0 (Materialise, Leuven, Belgium) using the following import settings:

Isometric sampling 19.99997

Pixel width – 456 -464 depending on sample

Pixel depth - 456 -464 depending on sample

It is important to note that these values are inverted as the grey value was inverted during the  $\mu$ CT reconstruction as canal identification was considerably easier when the images were presented in this way.

Segmentation of the canals was performed using the dynamic region growing tool, cropping the area of interest as much as possible to reduce the amount of unwanted data being transferred to the mask.

Dynamic region growing identifies connected voxels of similar radiodensity or Hu units. To region grow the pulpal space a minimum value of 10,000 HU and a maximum value of 50,000 was used to capture the entire pulpal space. Such a range was necessary to completely capture the pulpal anatomy.

The mask was then rendered in the 3D preview indicating region growing had extended beyond the apical foramen. To remove this extraneous data, the edit mask tool was selected and the erase function using the lasso tool was used to removed peripheral voxel that were not part of the region of interest.

After editing the mask to isolate the pulpal space, the mask was converted to a solid 3-dimensional object using the custom settings:

The Mimics centreline function creates a best fit centreline within a tubular 3-dimensional object. To ensure correct calculation of this centreline the 3-d object must be completely solid. Incorrect thresholding or dynamic region growing can result in the inclusion of voids within the object leading to an inaccurate centreline being calculated. This occurred in the initial attempts at dynamic region growing the pulp space. This was corrected by lowering the minimal Hounsfield unit threshold. However, this lead to a greater volume of unwanted data being included in the mask during the growing process and therefore required more mask editing before conversion to a 3D object.

The centreline was calculated using the analyse centreline function using the following settings

- Smoothing: 0.5
- Resolution: 39.999  $\mu\text{m}$
- Centreline point distance: 100  $\mu\text{m}$

At sections of the canal which were particularly oval the program calculated multiple centrelines. To simplify main centreline, which extended from the most coronal aspect of the canal to the most apical extent, was used.

## Morphometric analysis

The canal was studied using the 3d\*\* model, general features such as canal length, abrupt changes of size of the lumen, loops, anastomoses and changes of canal curvature were described.

The canal configuration was recorded and the number of canals from a coronal to apical direction. If possible, this was matched to existing canal classification systems such as Vertucci (1984).

Particular features were marked using the Analysis features in Mimics. The mid buccal point of the incisal edge, the most coronal part of the root canal and the very tip of the apex were marked using the Point tool in 3D mode. Measurements were obtained in the sagittal plane using the previously placed markers. Checking and refinement for these measurements was then performed using the 3D model. Anatomical measurements were then obtained for the length of the tooth and the distance from the incisal edge to the most coronal aspect of the pulp and, if present, the distance to any isolated portion of pulp present more coronally. If an isolated portion of coronal pulp existed that was not contiguous with the main canal, the distance to this was also measured.

Canal length was analysed using the Spline Analysis function. This allows a three-dimensional line (Spline) to be placed along control points placed upon the canal from the most coronal to most apical part. This can then be measured to give the canal length. The use of the centreline for this function showed too much variability due to the centreline calculation in very elliptical parts of the canal or different canal configuration where multiple centrelines were created by the software.

Analysis of the canal dimensions and morphology was performed using the measure function upon the main calculated centreline. Measurements were exported using the export function within Centreline properties.

The following parameters were calculated :canal circumference, minimal diameter of lumen, maximal diameter of lumen, best fit diameter of lumen and ellipticity of canal (see table 4-2)

Dimension	Definition	Unit
Cross sectional area	Cross sectional area of canal in axial section [see fig 3-4]	$\mu\text{m}^2$
Circumference	circumference of canal periphery [see fig 3-4]	$\mu\text{m}$
Minimal diameter	smallest diameter to contact opposing walls of canal [see fig 3-4]	$\mu\text{m}$
Maximal diameter	largest diameter to contact opposing walls of canal [see fig 3-4]	$\mu\text{m}$
Best diameter	calculated diameter based on mean of distances to diametric opposite walls of canal [see fig 3-4]	$\mu\text{m}$
Ellipticity	calculation of deviation from perfectly circular canal cross section	unitless

Table 3-2. Dimensions calculated from centrelines of the rendered canal spaces in Mimics software. Note that these dimensions are calculated from values perpendicular to calculated centreline.

This was then exported using a comma delimited text file (.csv) which allowed importing in Microsoft Excel (Microsoft corporation, Redmond, Washington, United States).

To assess canal concentricity the most apical point of the CEJ was identified on the axial plane. The Measure Area function was used to trace the outline of the root and the centroid of the root in the axial plane was automatically calculated. The location of the canal was then assessed in relation to the centroid of the root. The centroid of one canal was unable to be calculated on Mimics for an unknown technical reason.

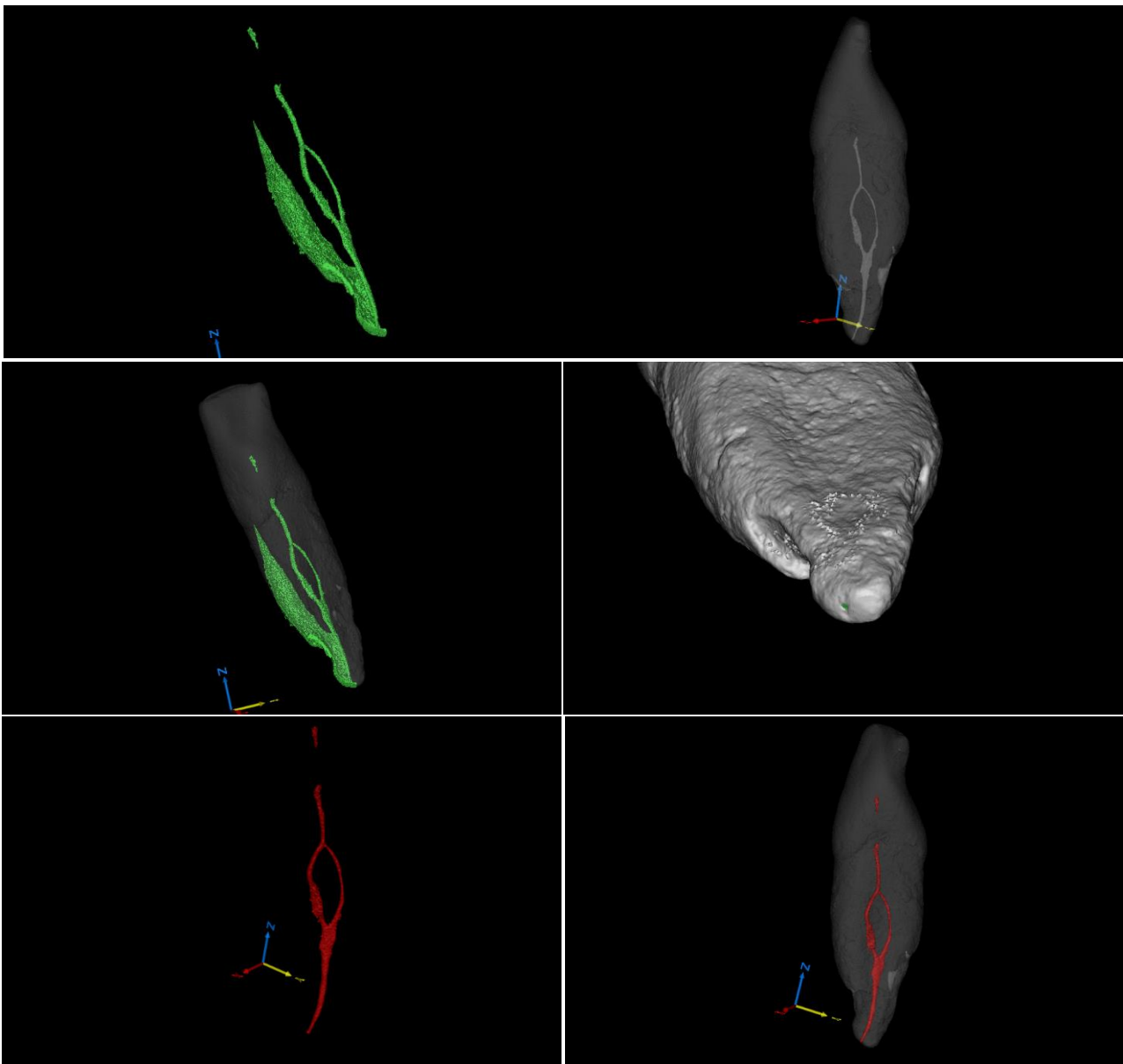


Figure 3--3. Creating of three-dimensional model of tooth and root canal system within Mimics software. Upper left: A mask is created of the canal system using dynamic region growing; upper right: A tooth model is created using thresholding prior to conversion to a three-dimensional object. Middle left: superimposition of canal mask and partially transparent tooth model. Middle right: use of the model to aid in trimming of canal mask to ensure correct length of canal. Bottom left: canal mask converted to three-dimensional object. Bottom right: superimposition of canal and tooth three-dimensional objects.

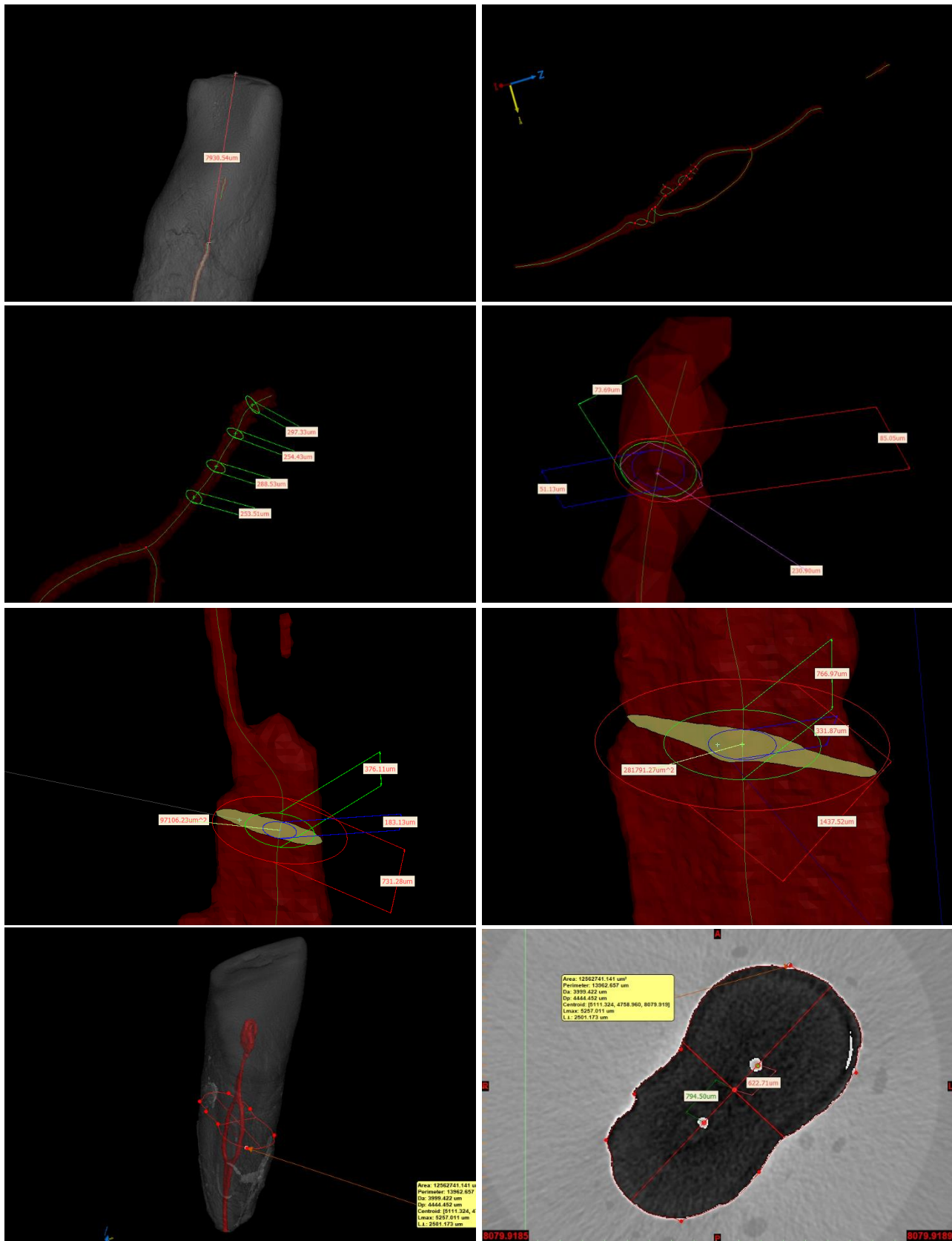


Figure 3--4. Morphometric analysis of the root canal. Top left: distance from incisal edge to continuous canal. Top right: creation of a centreline. Second row left: analysis of canal diameter at various points along canal. Second row right: Analysis showing best fit diameter (green), minimal diameter (blue), maximum diameter (red) and circumference (purple). Third row left: cross sectional area light green, not the change in elliptical shape in the more apical region of the canal. Third row right: note the differences in minimal, maximal and best fit diameters in elliptical canals. Bottom left: calculation of centroid point at canal bifurcation as shown on rendered model. Bottom right: analysis of canal distances from centroid point.

## Results

A processing error during  $\mu$ CT scanning resulted in corrupted files in four samples. Unfortunately, it was not possible to rescan these and so 4 teeth were excluded from the study leaving a total of 44 teeth on which analysis was performed.

### Overview of canal morphology

A canal was present in all teeth (n=44). Canal morphology showed considerable variation both in complexity of canal configuration and lumen size and shape.

An interesting feature, that was a common occurrence in the sampled teeth (n=14) was the existence of a coronally located canal that was not congruent with the main canal. In this sense it does appear that at certain points the canal can indeed 'obliterate' itself although the canal may possibly be less than this diameter and has not been identified at the scanning resolution of 20  $\mu$ m (fig 4.4). Smaller, more scattered, isolated spaces located coronal to the main canal were also observed although it is not clear if these were remnants of pulpal space or artefact of storage as some were close to the outer surface of the tooth. However, these spaces were extremely small and did not affect the analysis of the canal proper, so it is unlikely that their presence adversely affected the general morphological findings. Canal cross section was also very variable with some lumen almost perfectly circular in cross section with others very broad or elliptical.

### Morphometric analysis

Mean tooth length was 20.32 mm (SD = 1.54) whilst the average canal length was 13.60 mm (SD=1.72). See table

#### *Diameter of canals*

Canal diameter ranged widely from 27 to above 4617  $\mu$ m (see tables 4.3 and 4.4). These data should be viewed cautiously as they are calculated using the centreline function within Mimics. In areas of complex cross sectional shape the program calculates multiple centrelines that may not follow the long axis of the tooth thus the diameter reading maybe at an oblique angle obscuring the actual

dimensions of the canal. Extraneous centrelines were deleted to simplify analysis, but the centreline path could not reasonably be altered.



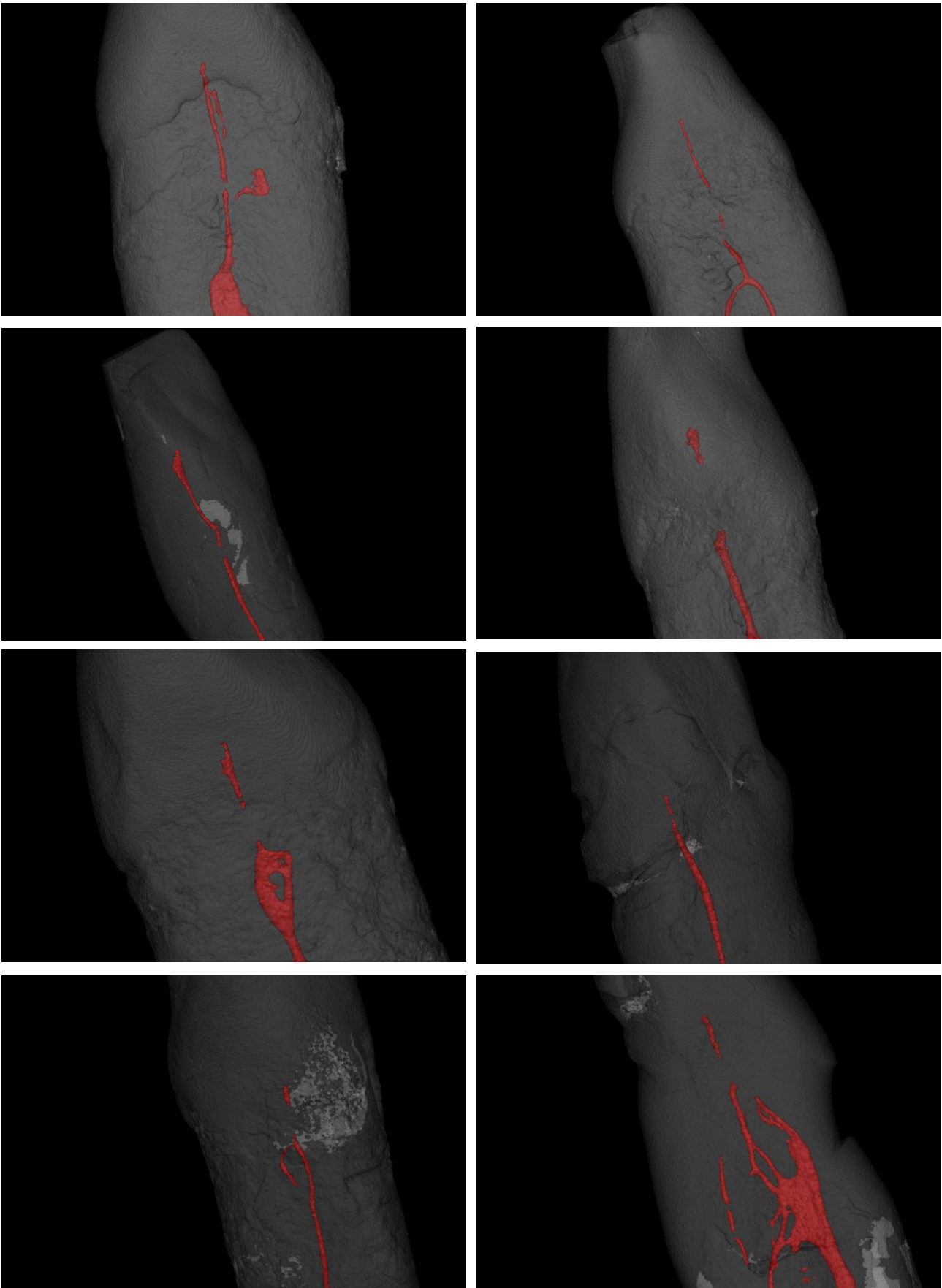


Figure 3--5. A number of samples demonstrated an isolated pulp space. These occurred almost always above the CEJ with a mean distance of 776 from the contiguous pulp space.

*Distance from incisal edge*

The average distance from the incisal edge to the first part of continuous canal was 6.5 mm (SD = 1.69). If there was an initial isolated pulp space (n = 14) the mean distance to the incisal edge was 5.38 mm (SD = 1.07) with the mean distance to the continuous canal 775.8  $\mu\text{m}$  (SD = 595.3).

*Canal concentricity*

Adhesions on the root such as cementum made formal analysis of canal concentricity with the root difficult but observationally the root canal did appear to be centrally located in most instances. Selected cross sections were analysed using the Area measurement tool in Mimics allowing the centroid of the root to be calculated. In the samples examined the lumen of the root canal was close to or on the centroid point supporting the idea that root canal wall thickness is relatively uniform. In cases where two or more canals the canals were obviously not both located at the centroid but did appear to be centrally located on the bucco-lingual axis.

*Presence of a canal at the level of the CEJ*

In all samples a canal was present at the level of the most apical part of the CEJ.

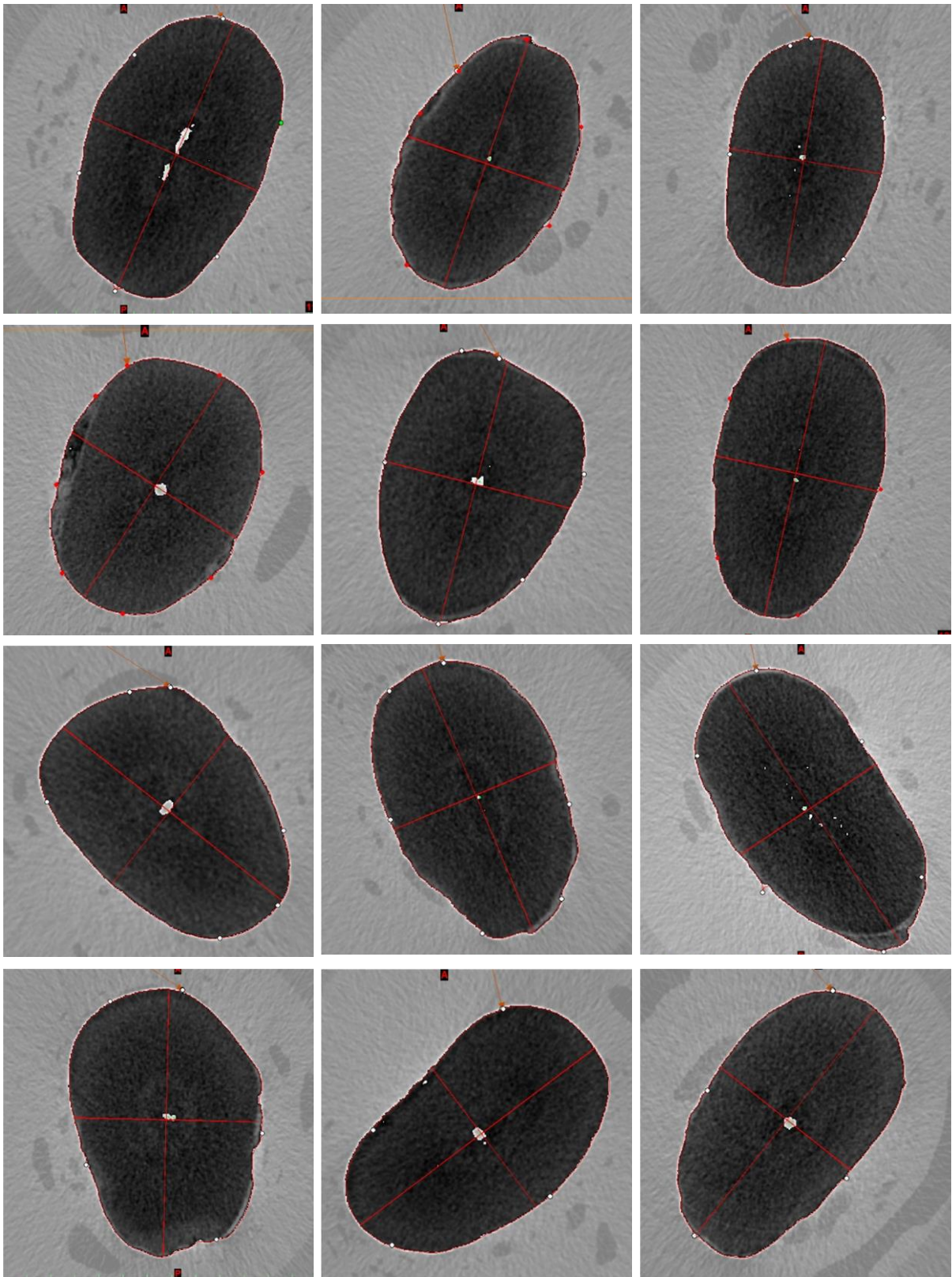


Figure 3-6. Samples of  $\mu$ CT axial sections of teeth at the lowest level of the CEJ. The intersection of the mesio-distal and bucco-lingual lines represents the centroid of the tooth at that level. Most sections demonstrate the lumen of the canal is located either on or in close proximity to the centroid of the root.

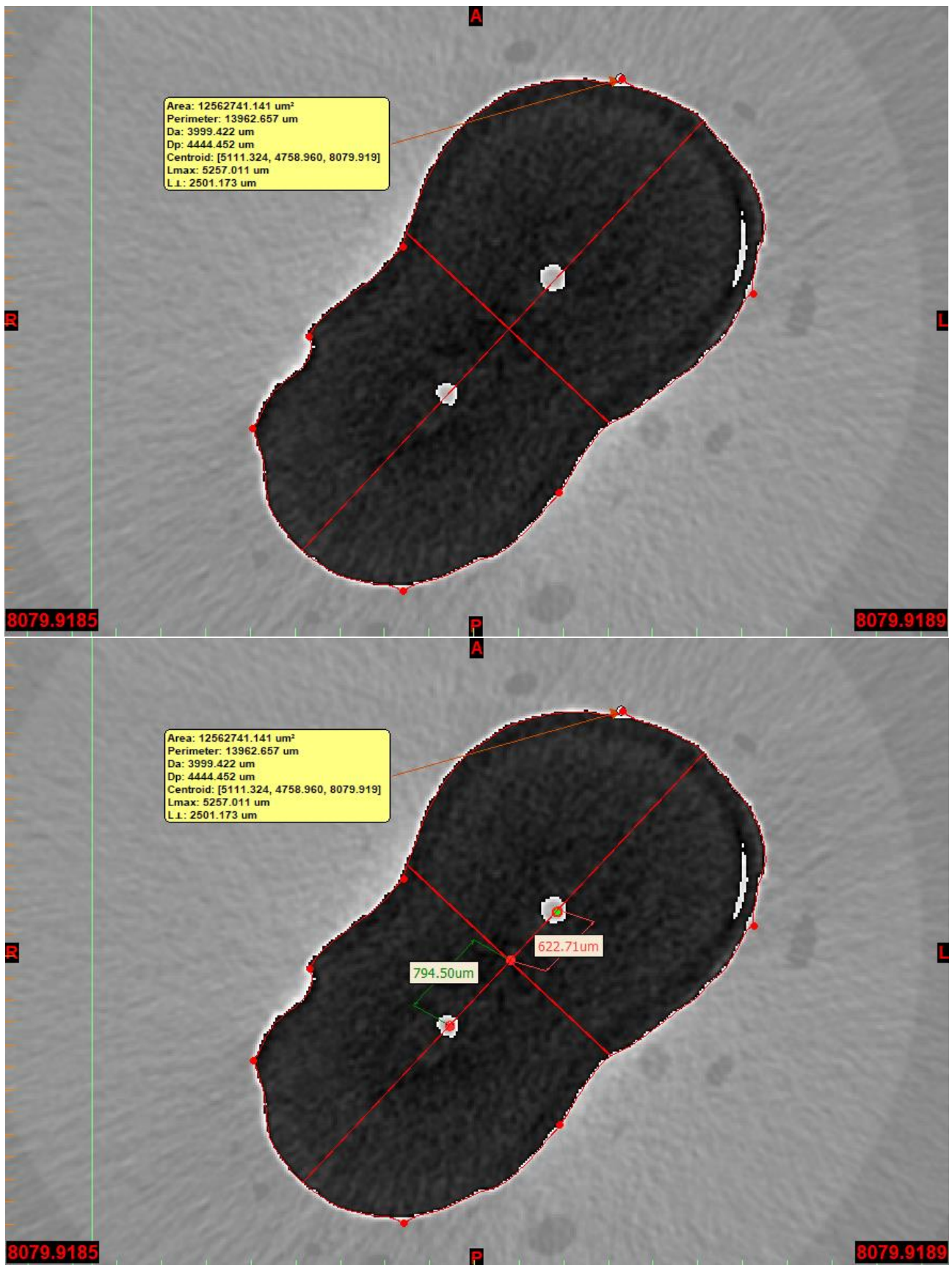


Figure 3-7. Analysis of laws of symmetry proposed by Krasner and Rankow (2004).

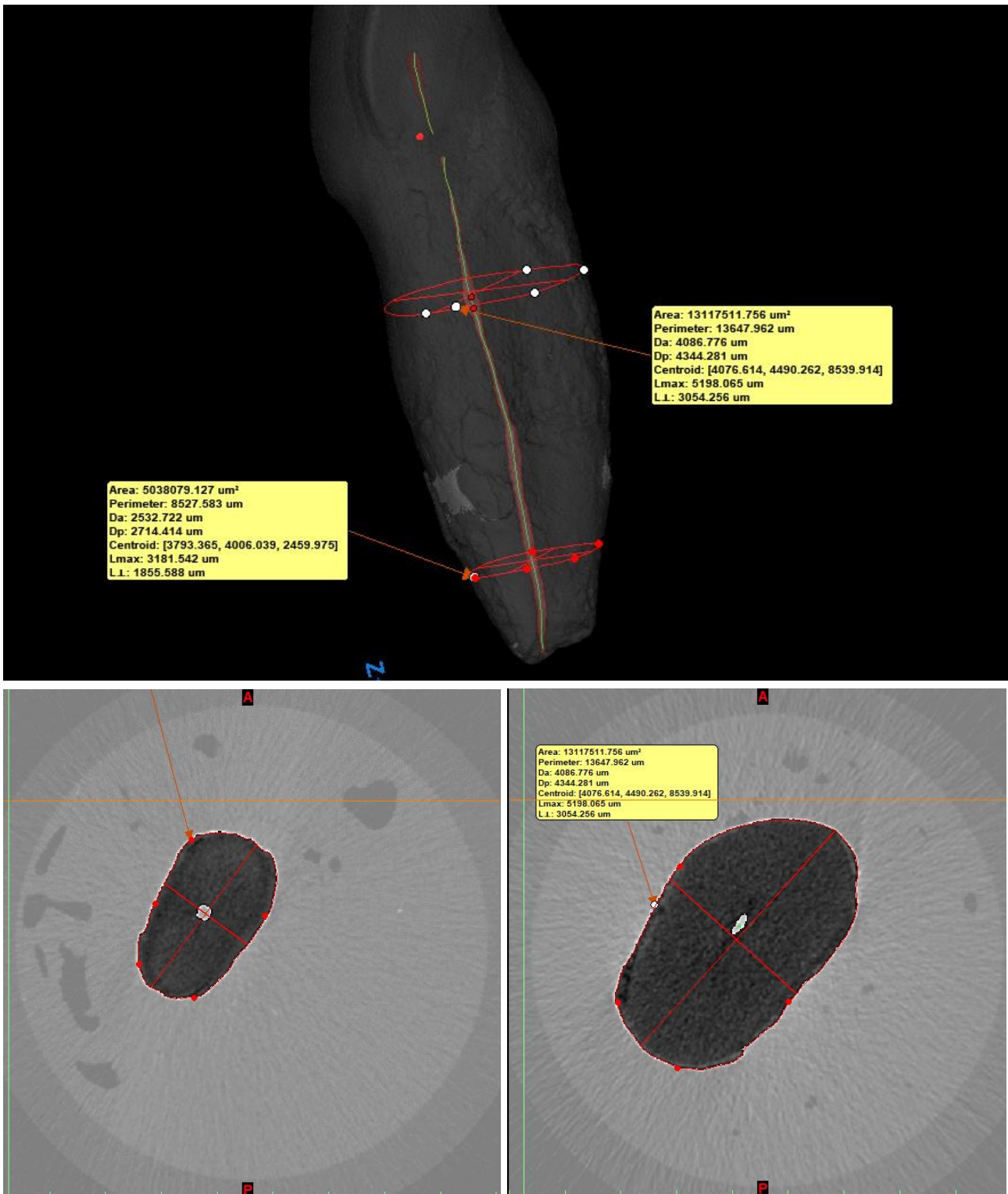


Figure 3-8. The position of the canal lumen in relation to the centroid of the root is not constant throughout the root length. In this tooth the lumen is less concentric in the coronal 1/3 of the root whilst in the apical 1/3 the canal is almost exactly in the centre.

### Canal configuration

Canal configuration varied from simple to extremely complex. Indeed, some canals were impossible to classify according to Vertucci (1984).

The most common configuration was a Vertucci class I (n=17) followed by Vertucci class III (1-2-1, n=11) pattern and then class V (n=4). Instances of extremely complex canal anatomy were also seen including one tooth that displayed a configuration of 1-2-1-2-4-5-3-4-3-2-3-2-1 (fig 4-8, *bottom right*)

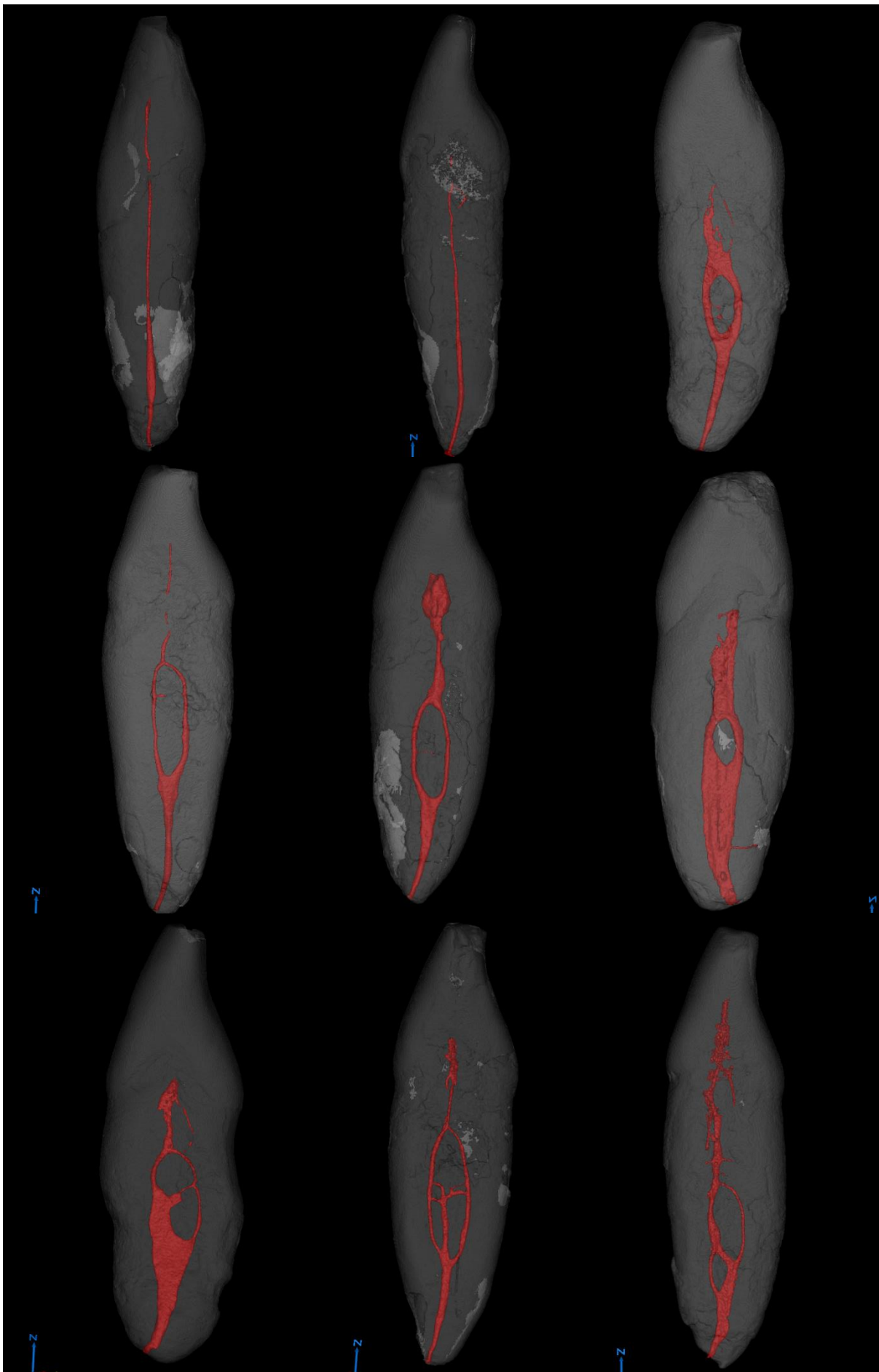


Figure 3-9. Canal anatomy of the samples ranged from very simple single canals to highly complex configurations that were not classifiable using most existing systems.

Chapter 3 Morphological description of calcified canals using micro computed tomography

	Length tooth (mm)	$\mu$ CT distance CP-IE (mm)	Continuous to apex?	$\mu$ CT to IP-IE (mm)	Canal length (mm)	Canal classification	DFit (max) ( $\mu$ m)	DFit (min) ( $\mu$ m)	DFit (CP) ( $\mu$ m)
1	22.3	8.62	N	7.14	14.13	1-2-1	335	64	67
2	18.9	3.43	Y	n/a	16.03	1-2	764	63	64
3	20.3	4.55	Y	n/a	16.02	1	411	45	87
4	18.6	4.25	Y	n/a	14.53	1-2-1-2-2-3-2-1	4247	145	145
5	22	9.68	N	6.02	13.28	1-2-1	233	84	96
6	19.7	6.85	Y	n/a	12.98	1-2-1-2	493	98	140
7	19.4	7.30	Y	n/a	11.73	1-2-1	1123	107	107
8	-	-	-	-	-	-	-	-	-
9	19.8	7.26	N	5.01	12.31	1-2-1-2-1-2-1-2	4617	63	512
10	20.1	6.59	Y	n/a	13.02	1	383	116	124
11	17.2	3.86	Y	n/a	13.04	1-2-1	1396	96	133
12	22.8	9.2	N	6.85	13.42	1-2-1	1128	102	102
13	18.41	5.73	Y	n/a	13.92	1-2-1-2-1-2-1-2-1-2-3	3993	27	94
14	21.4	7.87	N	4.81	13.75	1-2-1	1111	122	252
15	19.5	7.55	Y	n/a	11.78	1-2	503	123	123
16	20.2	6.77	Y	n/a	13.19	1	462	179	179
17	20.1	7.7	Y	n/a	12.03	1	568	211	112
18	23.2	6.1	Y	n/a	17.52	1-2-1-2-4-5-3-4-3-2-3-2-1	1398	107	359
19	23.4	8.7	N	4.22	14.66	1	1398	157	168
20	22.8	6.4	Y	n/a	16.33	1	723	113	120
21	21.4	8.39	N	5.44	13.31	1	444	90	206
22	20.0	5.71	N	4.82	14.02	1-2-1-2	955	108	123
23	20.2	7.25	N	6.55	13.21	1-2-3-1	780	100	100
24	19.3	5.76	Y	n/a	13.61	1	771	75	75

Table 3-1 Morphological data. CP-IE is the measurement from the pulp space that is contiguous to the apex. IP-IE. Some samples had initial pulp space not connected to the contiguous pulp. In those samples the distance to this initial pulp to the incisal edge (IP-IE) was also measured. Canal length was calculated from the spline function whilst canal configuration was assessed using the rendered 3D model of the pulp space as well as the axial sections. DFit (max) and DFit (min) are the maximal and minimum best fit diameters along the canal length. DFit (CP) is the best fit diameter at the most coronal point of the continuous canal. Teeth numbers in red were used in the later study comparing canal identification using phosphor plate radiographs and CBCT images.



Chapter 3 Morphological description of calcified canals using micro computed tomography

	Length tooth (mm)	$\mu$ CT distance CP-IE (mm)	Continuous to apex?	$\mu$ CT to IP-IE (mm)	Canal length (mm)	Canal classification	Dfit (max) ( $\mu$ m)	Dfit (min) ( $\mu$ m)	Dfit (CP) ( $\mu$ m)
25	19.0	4.56	Y	n/a	14.98	1-2-1	1243	175	446
26	20.3	7.49	N	3.55	13.71	1-2-1	1309	16	97
27	20.3	7.60	Y	n/a	13.51	1-2-1	3793	53	106
28	22.3	7.92	N	5.93	14.4	1-2-3-2-3-2-1-2-1-2	2339	99	206
29	21.9	7.14	N	5.97	14.67	1-2-1-2-1	962	95	139
30	17.8	2.50	Y	n/a	15.59	1-2	670	78	78
31	18.8	5.59	N	4.88	13.27	1	1102	43	67
32	19.2	6.76	Y	n/a	12.05	1-2-1-3	1500	72	87
33	19.9	5.81	Y	n/a	13.79	1	1777	71	77
34	18.1	6.61	N	4.13	11.31	1	353	52	123
35	-	-	-	-	-	-	-	-	-
36	17.8	5.62	Y	n/a	12.12	1-2-1	4970	205	206
37	19.0	8.58	Y	n/a	10.47	1	449	131	131
38	20.4	6.86	Y	n/a	13.37	1	280	54	161
39	20.1	3.81	Y	n/a	16.36	1	3367	92	216
40	20	6.81	Y	n/a	12.96	1	320	147	162
41	20.1	7.95	Y	n/a	12.12	1	441	220	220
42	-	-	-	-	-	-	-	-	-
43	21.1	4.34	Y	n/a	16.76	1-2	552	81	84
44	21.9	5.21	Y	n/a	16.91	1	540	144	172
45	21.4	7.46	Y	n/a	14.01	1-2-3-2-1	4460	94	157
46	22.1	8.36	Y	n/a	13.59	1-2-1	403	150	176
47	21.6	3.72	Y	n/a	18.18	1-2-3-2-1	2547	80	998
48	-	-	-	-	-	-	-	-	-

Table 3-2. Canal measurements continued from table 3.

## Discussion

A canal was present in all teeth. Complete obliteration of the canal is extremely rare but maybe associated with specific systemic conditions. Piattelli and Trisi (1993) reported a case of almost complete calcification (obliteration) of an upper first molar in a patient with rheumatoid arthritis although the longitudinal method of sectioning could be argued to be a less effective way of detecting a canal lumen when compared to axial sectioning. Other conditions such as sclerodermatous chronic graft versus host (cGVHD) (Gomes *et al*, 2016) and progressive systemic sclerosis (Jung *et al*, 2013) have also been reported although these are often reports based on radiography alone the real extent of calcification within these teeth is unknown and it is likely that a lumen is present. Certain conditions such as Dentinogenesis Imperfecta Type II may appear to show complete obliteration of the pulp canal space but a recent polarized microscopy and  $\mu$ CT study (Davis *et al*, 2015) has shown that there are extensive networks of tubular structures within the pulp canal space. It has been postulated that these tubular networks are the remnants of the pulpal capillary network that has undergone calcification and explains why seemingly pulpless teeth may develop apical periodontitis and abscesses. It therefore seems likely that obliteration of the pulp canal space, in its true sense, does not occur and that some small lumen does remain. Indeed, on the basis of the above study it maybe that the pulp regresses relatively little from the level of the CEJ but instead undergoes a narrowing of the lumen which results in the radiographic appearance of absence or recession which greatly reduces the chances of clinically locating the canal. In some samples (n=14) there appeared to be isolated pulpal space not contiguous with the main canal. These were entirely located in the crown or coronal one third of the root so in these teeth at specific points it could be argued that obliteration has occurred. However, this may be due to mineralisation with the larger pulp chamber becoming 'pinched off' from the smaller canal space

## Comparison with previous $\mu$ CT and histological studies

Whilst  $\mu$ CT is a very useful technique that is not invasive to the sample, the question of the canal contents is unclear. A previous study by Lunderg and Cvek (1979) showed that some traumatised teeth exhibit significant deposition of collagen and also hyalinization. It would be incautious to attribute the radiolucency of the pulpal space to either necrotic pup tissue or simply empty space

and histological verification of the contents would be useful. The clinical relevance of this is the degree to which each of these tissue types presents as an impediment to negotiation of the full length of the canal which is a necessary technical aim of non-surgical endodontic treatment.

Correlation of  $\mu$ CT with histological investigations is therefore warranted to determine if radiolucent tissue such as collagen or hyaline maybe present. Given that the specimens in the above study were disinfected using an enzyme-based product and stored within thymol it is likely that any tissues within the root canal would likely be degraded and may be of limited value in determining the above question. A future study, using tooth samples preserved in formalin would overcome these limitations but it is likely that obtaining such samples would be difficult.

### Isolated pulp space

The existence of a coronally located incongruous root canal in 14 cases (32%) is an interesting finding not previously reported in the literature. There is the possibility that a canal still exists but hasn't been detected at the 20  $\mu$ m resolution of the scan but the question still remains as to the reason for such morphology. Pulpal capillaries may only be 3-7  $\mu$ m in diameter (Harris and Griffin, 1971) so theoretically a capillary loop may still be able to connect an isolated area of odontoblasts via a canal lumen less than 20  $\mu$ m. A more probable explanation may however be areas of pulp tissue that fails to mineralise or are cut off from vascular supply during the mineralisation process. Localised necrosis could also explain these findings; however, some teeth showed no signs of restorative procedures or particularly marked wear so the cause for any postulated necrosis is unclear. In many of the cases the isolated pulp space is located coronal to the CEJ, so this may represent a niche of the pulp chamber or a pulp horn that became walled off during the mineralisation process.

The clinical significance of such findings likely depends upon the depth of the disjointed canal. Given that most are located coronal to the CEJ and the distance between the end of the isolated pulp space and the beginning of the congruent canal is an average of 775.8  $\mu$ m

In some cases, an isolated root canal was also noted (md005, md0027, md0028, md0045) laterally to the main canal. In all cases this was on the lingual aspect and may possibly be remnants of the lingual branch of the canal which has become isolated due to extensive calcification.

Some canals unclassifiable using existing systems and exhibited unusual anatomy. Ahmend et al has proposed a new system that maybe flexible enough to accommodate unusual configurations whereby the tooth is first classified by tooth number (TN) root number and then each individual root canal is classified from the canal orifice to apical foramen for example:

**<sup>3</sup>26 MB<sup>2-1</sup> DB<sup>1</sup> P<sup>1</sup>**

Indicating this is the UL6 with 3 roots and MB root having 2-1 root canal classification whilst the DB and P roots have a single root canal. Such a system is somewhat cumbersome, but it mitigates for shortcoming of previous systems such as Vertucci (1984), Weine (1969) and Gulabavala (2001, 2002). In some cases, the anatomy was so complex that it could almost be considered unique and therefore the Ahmend system may be useful when classifying these teeth.

Kuyk and Walton (1990) who analysed radiographically invisible or indistinct canal using sectioning methods reported a canal in all teeth and no lumen was less than 100 µm. Contrary to that study this study reveals several canals with the lumen smaller than this. This difference maybe attributable to the different method of canal investigation using µCT rather than histological sectioning and thus further study using sectioning of specific teeth to correlate the radiographic findings with the histological evidence is recommended.

Clinically these findings are important as the smallest endodontic file has a tip size of 60 µm although with any attempt to negotiate a canal, the taper as well as the tip size of the instrument plays an important role.

## Kranser and Rankow laws and calcified lower incisor teeth

It appears from this study that the laws proposed by Krasner and Rankow (2004) do seem to hold true with mandibular incisor teeth. Canals are present at the CEJ; however, some canals were so small that it may not be possible clinically to instrument them. Where one canal exists, the law of concentricity does also seem to be obeyed, however this seemed to vary along the root length. Although no subject to formal analysis the canal appeared to become more concentric in the more apical regions of the root. Where two canals exist, they appear to follow the rule of symmetry

## Limitations of study

Although this study has attempted to improve upon the methodology and techniques of previous studies, there are still some limitations which should be discussed. The study was conducted using only one operator with the possibilities of observer/recorder bias. The samples themselves of lower anterior teeth may give a general overview but it was very difficult to determine if the incisors were central mandibular incisors or lateral incisors. Whilst similar these teeth have been shown to have different frequencies of canal anatomy which could affect the results. Furthermore, the dental history of these teeth was unknown as they were obtained from anonymous donations. No information on age, sex or events such as trauma could be determined. Therefore, whilst the canal lumens show varying degrees of narrowing, the aetiology behind this process is unknown. A number of teeth showed wear both on the incisal edge and cervically and it is possible that this was a contributory

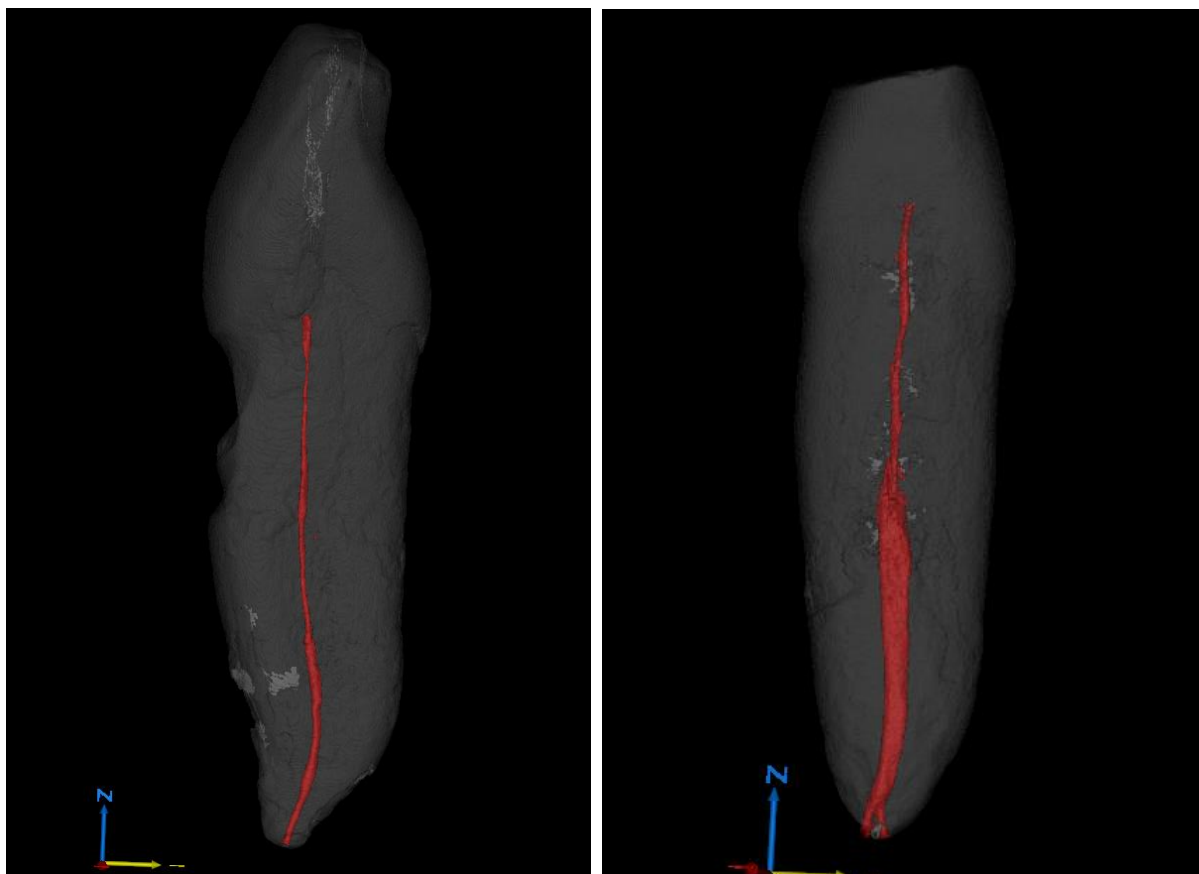


Figure 3-9. Although the aetiology of calcification of canals was unknown in the study group a number of samples showed signs of wear, either exhibiting incisal attrition or cervical abrasion. It is possible that some narrowing of the canal lumen is a result of reactionary changes in the dentine in response to these wear patterns. Upper left: note the narrowing of the pulp in the region of the cervical wear with a larger pulp space above. Upper right: marked incisal attrition with distinct narrowing in the coronal one half of the root, notice how the canal abruptly increases in diameter.

factor to the formation of tertiary dentine (see fig. 4-8) but without more detailed longitudinal data this will remain speculation.

A resolution of 20  $\mu\text{m}$  was chosen for  $\mu\text{CT}$  scanning as this was considered high enough to capture clinically relevant details without the excessive time for scanning that higher resolutions require. However, it is possible that in regions that some canal was not observed a higher resolution scan may have allow identification of extremely small canals. Additionally, similarities in contrast, ring artefacts and micromovement of the sample during scanning may have created artefact that would affect the results. Every effort was made to ensure this was minimised, but their presence cannot be entirely excluded.

The Mimics software may also introduce some errors. Thresholding and dynamic region growing are useful tools but are not without their drawbacks. Dynamic region growing allows rapid segmentation of the connected pulpal space but as has been shown, the existence of separated pulpal space is not

detected using this method and it is necessary to perform thresholding over a larger area to detect these. The centreline function also has limitations especially in canals which are irregular or particularly elliptical as multiple centrelines are created in these structures. Consequently, obtaining meaningful measurements on the canal diameter becomes limited. Therefore, using a combination of best fit diameters and cross-sectional areas is likely to provide the most clinically relevant information.

### Future studies

In vivo/ex vivo studies perhaps with individuals with known history of dental trauma would help relate aetiology of the calcification with the radiographic findings. This would likely be a difficult study to carry out as obtaining extracted teeth would probably be only be possible in those extensively damaged by the trauma, such teeth tend to suffer more severe trauma resulting in rapid necrosis of the tooth whilst those showing calcification usually have received less traumatic injury. Furthermore, anterior teeth are rarely extracted for orthodontic reasons so obtaining such samples would be difficult. Further cadaver studies similar to those conducted by Kuyk and Walton (1990) maybe bring a further level of realism for intraoral radiography whilst allowing samples to be taken en-bloc for  $\mu$ CT comparison but also present difficulties in obtaining suitable teeth with extensive calcification. A compromise maybe the further development of clinically realistic phantoms using teeth of know dental history.

## Chapter 4 – A study comparing PA radiographs against CBCT images in the determination of the location of the sclerotic/calcific root canal systems

### *Introduction*

#### Why does canal identification matter?

Endodontic access and negotiation of calcified canals is a well-known challenge (McCabe and Dummer, 2012). During the planning phase of endodontic treatment, the clinician must select the correct angulation of access and distance to the initial pulpal space. The use of a pre-operative radiograph is considered an essential component of this process. As well as allowing assessment of the attachment levels and periapical status, radiographs also provide information on the visibility of the canal, any recession of the pulpal space, canal configuration and curvature. This then allows the clinician to anticipate the difficulty of the procedure.

The management of calcified canals requires information about the level at which the canal is likely to be first encountered. Thus, if the access cavity is cut to this identified point the clinician can then attempt to cannulate the canal with a small endodontic file. If they are unable to do this then knowing the access is at the correct depth would then guide them to look laterally in order to locate the canal rather than prepare a deeper cavity. Creating a deeper access risks both perforating the root and also weakening the tooth due to excessive removal of tooth structure (Clark and Khademi, 2009).

Using extracted teeth Molven 1973 has shown a correlation between invisibility of canals radiographically and the inability to instrument them. The study however, had a fairly limited sample size and employed an antiquated instrumentation technique compared to modern methods.

Imaging of such fine structures is limited by a number of factors such as spatial and contrast resolution which varies between modality (Patel et al, 2016) which have been discussed in the previous review of the literature. Therefore *in vitro* investigations comparing the differences between



conventional radiographs and CBCT images require that soft and hard tissue are emulated accurately enough to produce images that are comparable with those from real subjects.

### Existing phantoms

Phantoms are commonly used for the study of dosimetry, quality assurance, training and imaging studies. Although a number of commercially available phantoms exist, the objective of this study was to develop a new type of phantom that would allow easy substitution of a lower incisor tooth in order to investigate differences between digital periapical radiology and CBCT in calcified teeth. Presently no such phantom is available and therefore it was necessary to design, create and validate a new device to achieve these requirements.

### The importance of replicating soft tissue

To infer meaningful conclusions, *In vitro* research requires a close approximation to the real-life situation as possible. The quality of a radiographic image is dependent on the number and energy of x-ray photons. These x rays are generated by accelerating electrons through a vacuum towards a tungsten anode. As the electron passes through the anode it maybe deflected and slowed down by the nucleus of a tungsten atom. The energy loss from this deflection and slowing is released as an X-ray photon. The proximity of electron to the nucleus determines the amount of deflection and deacceleration and as this varies, so does the result energy of the photon. The range of energies can be expressed in graphical form, known as the Bremsstrahlung spectrum.

When x-ray photons pass through biological tissue they have a probability of interacting with the electrons of the individual atoms. Interactions can be classed as either absorption, scattering or transmission. Absorbed x-rays result from displacement of an inner electron by means of the photoelectric effect and has no resultant effect on the image.

Scattered X-rays can be classed as Compton or Rayleigh scattering although only Compton scattering is relevant to image formation. This occurs when the photon interacts with an outer, loosely bound electron, causing both deflection of the photon and giving rise to ionising radiation. Scattering

is important to image formation because, as it has deflected, it does not give anatomically accurate information.

Transmitted X-rays pass through the tissue and contribute directly towards the image. The probability one of these interactions occurring is a function of the photon energy, the atomic number and electron density of the tissue and the physical density of the tissue. Soft tissue will attenuate the beam less than bone, enamel or dentine and therefore photons moving through soft tissue will be less likely to produce scattering or absorption.

Therefore, mimicking the attenuation of the x ray beam as close to the real-life situation by the phantom material is required to give a clinically realistic appearance.

A number of studies investigating the ability of CBCT to detect root canal system exist. The methods employed in these studies often involves placement of teeth with a putty material or perhaps the use of a dry mandible and attempt to replicate the soft tissue with a number of layers of wax or sheets of acrylic or sometimes nothing at all (Matherne et al (2008), Michetti et al (2010), Vizzotto et al (2013, 2015)) These methods are assumed to replicate the in vivo situation without any serious attempt to validate them. Examination of the images reproduced in these studies reveals images with high contrast and sharp spatial resolution. When compared with real clinical images, even those taken at high resolution, the latter do not demonstrate the spatial or contrast resolution of the former. The question must be asked therefore as to the whether such studies are over estimating the ability of CBCT to detect such fine structures.

### Existing soft tissue analogues

Water makes an excellent soft tissue replacement as it is almost the same radiographic density as soft tissue. Whilst this may be acceptable for simple dosimetry studies or radiographic studies involving only periapical radiographs, water is not suitable for construction of a CBCT imaging phantom as it is very difficult to create the correct anatomical dimensions that are likely to have an influence on image formation with this modality.

## Other material that have been tested include

Previous studies using phantoms have used a soft tissue analogue using a composite material called Mix-D. This material was developed by Jones and Raine (1949) to have the same electron density and effective atomic number as soft tissue.

It is created by mixing 60.8% paraffin, 30.4% polyethylene, 6.4% magnesium oxide, and 2.4% titanium dioxide to create a substance with an electron density of  $3.36 \times 10^{23}$  electrons/cm<sup>3</sup>. This is the same as water and is very similar to soft tissue. In addition, the material can be melted and applied to hard tissues to allow modelling of realistic soft tissue dimensions.

A problem with Mix-D production is achieving uniform dispersion of the metal oxides during its production. Oxides may settle during the cooling phase creating areas of increased radiopacity with surrounding material of radiopacity lower than that of soft tissue. This fails to replicate the radiodensity required for correct beam attenuation and creates an unrealistic appearance on the radiograph.

Brand et al (1989) addressed this problem with a process of cooling the mixture as small cubes and re-melting to produce uniform dispersion. This material could then be melted and applied like wax to build up the correct morphology or it could be cast into specific shapes.

## Aims of the study

The aim of the study was to determine if there was difference between CBCT and PA images at which observers first perceived the root canal, using the distance from the incisal edge as the primary outcome measure.

A second aim of the study was to determine the canal dimensions, using  $\mu$ CT, at the point at which canal was perceived on both PA and CBCT images

## Null hypotheses

H<sub>0</sub>: there is no difference between observer's ability to detect the most coronal part of the root canal space using either conventional periapical radiography or CBCT

## Methodology

### Phantom design

The phantom had to satisfy the following requirements:

1. The soft and hard tissue analogs are radiographically equivalent to the real-life tissues that they simulate.
2. The phantom will be dimensionally accurate around imaging as thickness of any material will affect beam attenuation.
3. The phantom can be assembled in such a way that allow the lower left lateral incisor tooth socket to receive a lower incisor to be studied.
4. The phantoms can be placed in a reproducible way in the Morita Accitomo CBCT machine
5. A long cone periapical radiograph can be taken of the lower left lateral incisor, in a reproducible way, within the phantom using a paralleling technique perpendicular to the mesio-distal plane of the incisal edge
6. A long cone periapical radiograph can be taken, in a reproducible way, within the phantom of the lower left lateral incisor using a paralleling technique at 15° distal to the mesio-distal plane of the incisal edge

### Modification of human mandible

A dry human mandible, edentulous apart from an impacted LR8, was modified to allow the placement of teeth in the anterior region. This involved the use of high speed diamonds and surgical length tungsten carbide burs to deepen the tooth sockets to allow a greater depth of root within to sit between the cortical plates. Teeth from the tissue bank were selected for the appropriate anatomical type and shape and were placed within the prepared sockets. The LL2 socket was deepened further to allow the selected lower incisor teeth to sit within the socket and allow as much of the root to sit within the bony housing, as possible.

Teeth other than the LL2 were joined together using cyanoacrylate glue to prevent further movement when the LL2 test tooth was changed and to maintain consistency between radiographs. Cyanoacrylate was used as it is effective, simple and radiolucent.

An impression of the entire mandible with teeth other than the LL2 in situ was taken using duplication silicone. A duplicate mandible was then created using polyurethane which could then be used to create the soft tissue phantom surrounding the mandible without risking damaging it.

### **Selection and testing of soft tissue analogues**

Mix-D was selected to be the soft tissue analogue as this has been validated within the literature, has an atomic number identical to water and can be cast into any shape required and is relatively easy to modify.

The production method was followed as described by Brand et al (1989). White Poly Wax (International Wax Refining Company, Inc., Valley Stream, New York) is no longer commercially available. However, the chemical profile of this material is extremely similar to other commercially available polyethylene waxes. An alternative polyethylene wax, Kerawax 2775 (Kerax, Chorley, England) was used as a substitute.

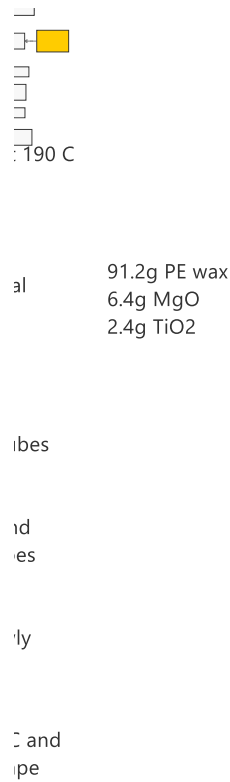


Figure 4-1. Production flow chart for Mix-D material. Despite meticulous adherence to this formula the settling of the metal oxides could not be eliminated. Therefore, attempts to manufacture and utilise Mix-D were abandoned in favour of an alternative material.

The wax was melted and 6.4 g of magnesium oxide and 2.4g of titanium dioxide were added per 100g of polyethylene wax. This was then stirred thoroughly, allowed to cool and solidify and then re-melted and recast into discs.

### Problems with Mix-D production

Several attempts to manufacture Mix-D during this study involved replicating Brand et al's (1989) methodology. Unfortunately, despite extensive efforts with casting and re-melting blocks of the mixture settling and aggregation of the metal oxides was still observed.

Thus, attempts to use this material were abandoned in favour of finding a substitute material that would have uniform radio density but would still appear as similar as possible to soft tissue.

A number of alternatives to Mix-D were trialled. Blocks of PMMA, dental carding wax and polyurethane were immersed in water and radiographs were taken vertically to assess the visibility of the material in water which was accepted as an appropriate density to represent soft tissue. In addition, the materials were placed in beaker of water and subject to a cone beam scan, if a material was not differentiable from water then it was considered to be a suitable soft tissue analogue.

Of the materials tested polyurethane appeared indistinct with water in both PA and CBTC images and therefore was concluded to be the most suitable and therefore was selected to create the soft tissue mask over the mandible.

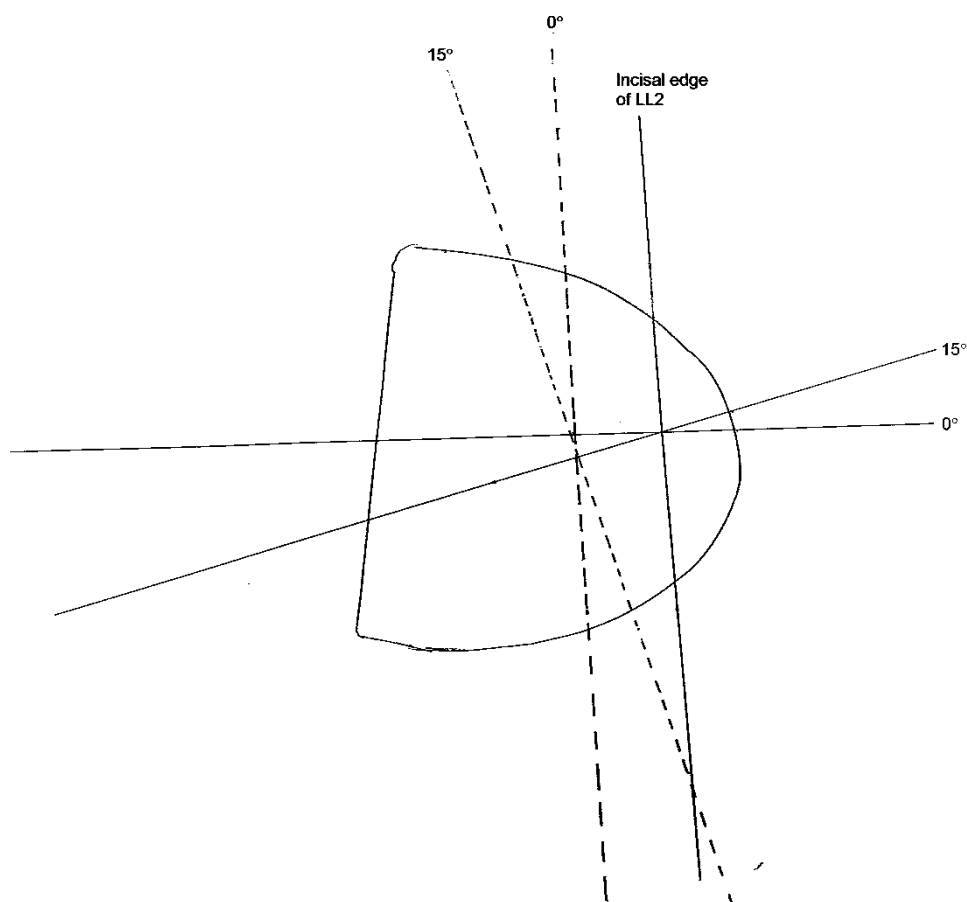


Figure 4-2. Design specifics of x-ray direction for the PA film holders and beam aiming device. The dotted lines represent the orientation of slots placed in the phantom base to secure phosphor plates. The solid lines represent the direction of the x-ray beam and therefore the position of the beam aiming device. Note that the angulation is relative to incisal edge of LL2 and not the film itself which is always perpendicular to the x-ray beam.

### Selecting Soft tissue dimensions

Soft tissue dimensions were calculated using a typical head and neck CT scan. The scan was selected on the basis of clinically normal appearance and appeared to be of average anatomical dimensions. The approximate dimensions were used when creating the soft tissue dimensions were Chin: 15mm, Buccal soft tissue: 20mm and Genial tubercle to pharynx: 60mm.

The phantom was then created to allow disassembly. First a base was created that allowed the mandible to sit with, posterior to this, slots were created to allow the placement of size 2 phosphor plate in perpendicular and 15° angulations to the incisal edge of the LL2. The chin rest attachment from the Accitomo was replicated using duplication silicone and a copy of the attachment peg was added to the base. This peg has a small slot at its base into which a centring pin locates, preventing rotation of the chin support. This allowed the phantom to be placed within the machine in a reproducible manner.

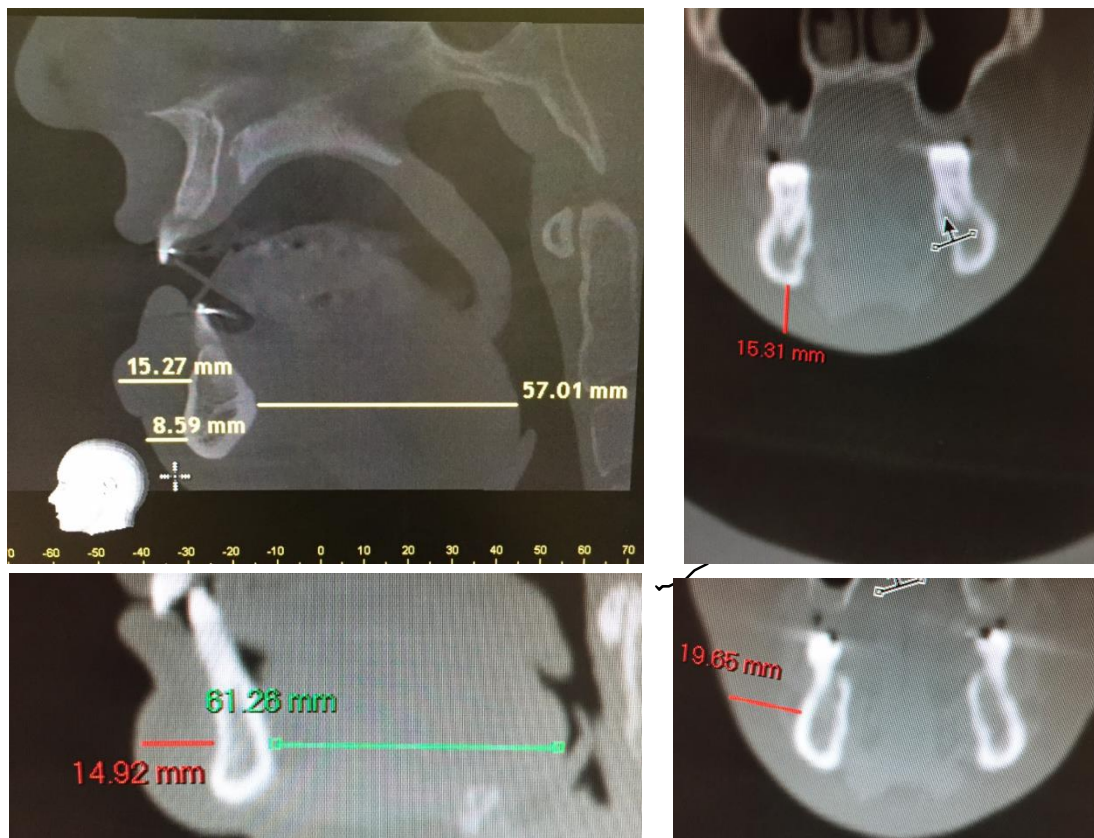


Figure 4-3. CT scans used to determine a typical soft tissue dimension for the phantom. As soft tissue vary a scan was selected based on an average looking appearance with clinically realistic dimensions.



This base was designed with locators to allow placement of a buccal soft tissue mask that covered the entire mandible and the teeth set within it up to the incisal edge.

Finally, a tongue replica was made to fill the space distal to the lower incisors to the pharynx, this also was created with indentations to allow this part of the phantom to be placed in same place in a predictable and consistent manner.

To reduce air spaces and replicate saliva, ultrasound jelly was used to fill spaces between the component parts.

### Design features to allow standardised PA images

The phantom was constructed to allow placement of a standard size 2 periapical film perpendicular to the lower left lateral incisor.

Two slots were placed on the base of the phantom, one at a 0° angle and the other at 15° angle to the periapical films

### Validation of phantom using conventional CT

The phantom was placed within a conventional medical CT scanner (Somatom Definition AS, Siemens Healthcare, Erlangen, Germany) using an exposure protocol of 120Kv, 120mAs and the Hounsfield unit value of the bone and soft tissue mask was calculated using Carestream Vue PACS (Carestream health, Rochester, NY). This was undertaken as conventional CT scanners allow direct measurement of the Hounsfield units in a particular volume of the phantom whereas CBCT does not. If the material showed HU values within the range of soft tissues it was considered a valid soft tissue analogue.

### Confirmation of suitability of phantom as a realistic analogue

Average CT number for acrylic and ultrasound jelly showed Hu values within soft tissue range of 0-100 with exact number varying depending on porosity in the specific area measured. A consistent measurement of 30-35 was gained when CT number for a 1cm squared area of acrylic was measured in an area without visible porosity.

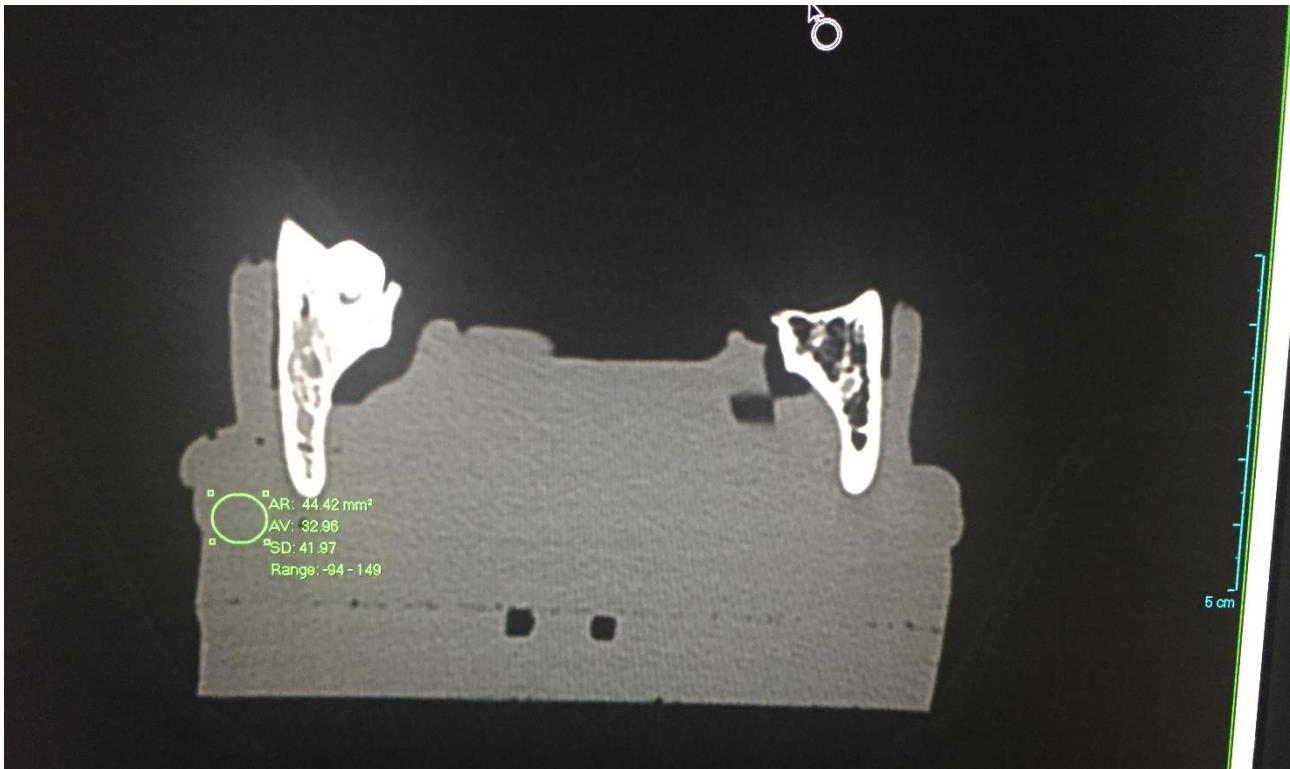


Figure 4-4. Medical CT scan of phantom showing real mandible in situ. A non-porous area of polyurethane was select to calculate the HU value which was in the range of actual soft tissue.

Tissue type	CT number (HU)
Soft tissue analogue:	12- 35
Bone (craniofacial)	200
Lymph nodes	10 to 20
Muscle	35 to 55
Fat	-120 – -90
Water	0

Table 4-3. Hounsfield units for soft tissue analogue with comparison values for craniofacial dental tissues.

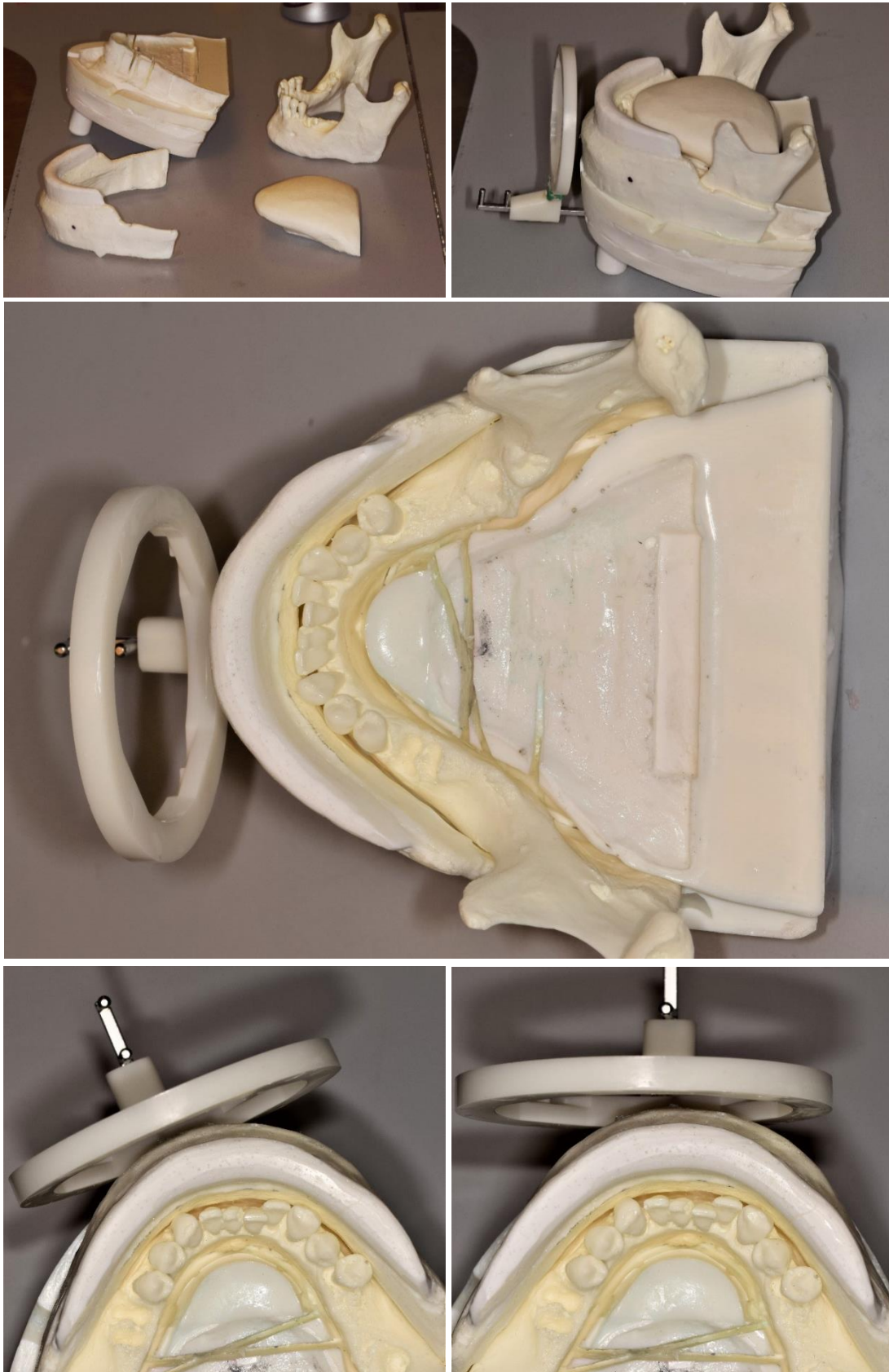


Figure 4-5. Top left: individual components for the radiographic phantom, mandible has been copied to allow fabrication without risk of damaging real mandible. Top right: assemble phantom with PA beam aiming device. Mid: top down view showing location recess for tongue and PA holder slots. Bottom: 0° and 15° angles for beam aiming device.



Figure 4-6. Top: phantom set up for PA radiography still within CBCT machine. Removal of the tongue analogue allows placement of phosphor plate and beam aiming device. Below: phantom in CBCT set up for scanning with tongue analogue in situ. Note the ultrasound jelly placed between soft tissue analogues to replicate saliva and to eliminate air pockets.

Chapter 4 A study comparing PA radiographs against CBCT images in the determination of the location of the root canal system

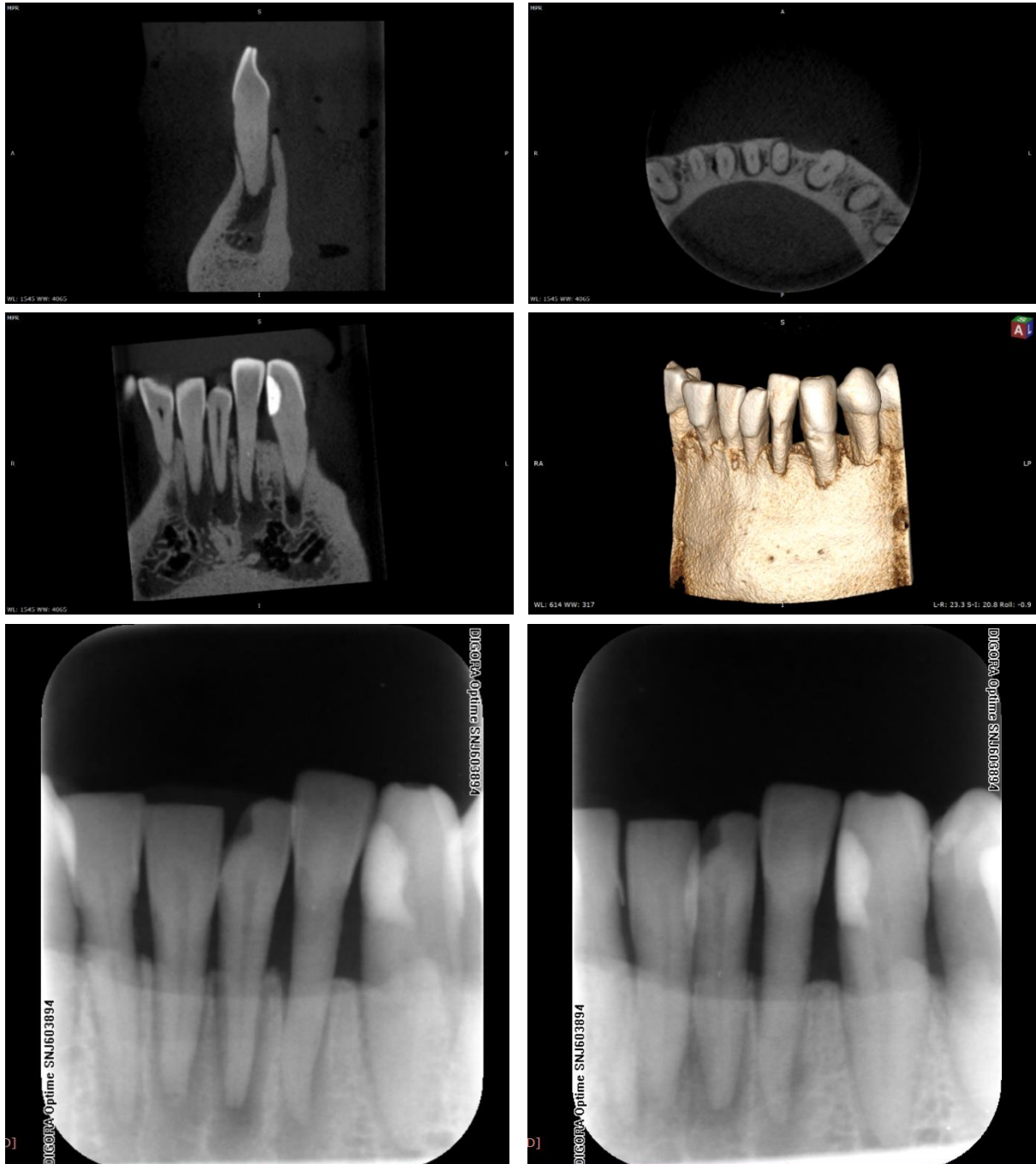


Figure 4-7. Images from small field of view scan using the phantom in Morita Accuitomo 170. Some small air pockets can be noted in the bony trabecula at the base of the mandible and under the canine due to insufficient soaking of the mandible which was rectified during the scanning for the canal identification study. Middle right: 3D reconstruction showing a 'clean' but clinically realistic scan with minimal artefacts but sufficient beam attenuation. Bottom left: 0° degree phosphor plate PA of the same tooth shown in the CBCT scan. Bottom right: 15° PA of the same tooth.

## Tooth selection

The teeth selected and studied using micro CT were used for this study as this allowed a gold standard against which the results from periapical and CBCT images could be evaluated. A total of 48 teeth from the  $\mu$ CT morphological study were used for the study.

## CBCT and PA devices

The CBCT scanner used in this study was the Morita Accuitomo 170 (Morita corp, Suita City, Osaka, Japan). This 4<sup>th</sup> generation unit is claimed to have a maximum resolution of 80  $\mu$ m and a 14-bit greyscale capability.

The x-ray unit model and type for obtaining periapicals was the Focus 50420-IMG (Instrumentarium Dental, PalDEX Group Oy, Tuusula, Finland).

## Optimization of scan settings

Scan settings were based on clinically realistic values. The phantom had previously been validated using conventional CT to calculate the HU values of the material and these were in the reference range of soft tissue. In addition, the phantom was also scanned in the Accuitomo 170 and using two independent examiners the images were deemed to be comparable with those from real CBCT images. After discussion the following settings were agreed upon:

Resolution: 80 $\mu$ m

Rotation: 360°

Scan time 17.5 sec

Tube current: 3.0 mA

Tube voltage: 90 kV

Field of view: 40 x 40 mm

## Periapical radiographs settings

kV and timing were selected on the basis of clinically realistic exposures. In a similar manner to the CBCT settings a number of periapical radiographs were taken and the images examined

independently by two observers to ensure the images appeared clinically realistic. The following settings were then agreed: see table 5-1.

Anode voltage	70 kV
Anode current	7 mA
Exposure time	0.08 sec
Inherent filtration	2.0 mm Al
Source to skin distance	305 mm
X-ray field	35 x 45 mm

Table 4-2. Settings of Focus x-ray generator.

### Image acquisition

After optimisation of the scan and PA settings the teeth were placed sequentially within the mandible LL2 (32) socket. Ultrasound jelly was used to mimic saliva and fill air spaces between the component parts of the phantom. The soft tissue masks were then placed over the mandible and the phantom was placed within the CBCT machine.

The area of interest was targeted using the sagittal, coronal and axial laser marker lines and a scout image was taken. A small field of view (40x40 mm) scan was selected with the LL2 in the centre of the field. The scan was then taken at the previously described settings.

After scanning a small stent was made by applying temporary crown and bridge material across the incisal edges of the incisor teeth, allowing the incisor tooth in the LL2 socket to be reproducibly placed in the same position. This then allowed all the CBCT scans to be completed after which the phantom was placed in a different radiography room with an X-ray tube for intra oral (Focus 50420-IMG, Instrumentarium Dental, PalDEX Group Oy, Tuusula, Finland).

Scans were reformatted using the Morita proprietary software and converted to DICOM files to allowing viewing on RadiAnt software (version 4.0.3.16415; Medixant, Poznan, Poland). These were coded and stored securely on a University of Liverpool computer.

To obtain the periapical images teeth were then placed back into the mandible and positioned using the composite splint taken after the CBCT scan, the x-ray tube was then aligned using the aiming ring attached to the base of the phantom. A phosphor plate (DIGORA accessory intraoral imaging



Figure 4-8. Set up demonstrating positioning of the phantom within the Morita Accuitomo 170 scanner and additional set up for periapical radiography. Note the slots posterior to the mandible in which size 2 plates could be placed at 0° or 15° from the perpendicular axis to the incisal edge.

plates (Sorendex, Tuusula, Finland)) was then placed in the holding slot at the base of the phantom in the corresponding 0° or 15° slot. The teeth were then radiographed at both 0° and 15° using the previously agreed settings.

Phosphor plate radiographs were then developed using the Digora system (Sorendex, Tuusula, Finland), coded to allow later identification and securely stored electronically.

### Image selection and randomisation

Two observers independently examined the images. Some images were excluded on the basis of a very visible canal on both the PA and CBCT image that was not apparent on the selection radiographs. As the study was investigating the use of CBCT in the identification of very small canals, the use of these teeth was argued to be of little benefit. The remaining images were then randomised using a stratified randomization method. Randomisation entailed the use of a randomly generated list using the Random.org website. The images were shown in the following order: 0° PA, 15° PA and CBCT and this was constant throughout. Therefore, the individual images were randomised within those groups so participants would be unaware of which 0° PA related to which 15° PA or CBCT and vice versa.

### Observer selection

Six observers were recruited from speciality training programs in Endodontics or Restorative Dentistry at Liverpool Dental Hospital based on a discussion with a biostatistician after collection of



data using three observers as an internal pilot. After a total of six observers were used the data were re-examined by the biostatistician and appeared normally distributed. All observers had spent a minimum of two years within their respective specialist training program.

### Observer set up

The experiment was performed in a radiologist reporting room using a diagnostic monitor (Barco MDNG-2121, Barco, Kortrijk, Belgium) set to 100% luminance. The room was darkened, as is standard for radiographic reporting, to allow maximum discrimination of grey values.

Images were displayed using RadiAnt DICOM viewer (version 4.0.3.16415; Medixant, Poznan, Poland) using the MPR function.

The images had then been randomised by one investigator and the images were shown to the observers by the other investigator to ensure double blinding of the samples.

## Instructions to observers/Calibration

Observers were calibrated using an instruction sheet provided before the experiment (see fig. 5-4). This explained the objective of the exercise and explained how to use the RadiAnt software to measure on the periapical image from the incisal edge to the most coronal point at which the root

**STUDY COMPARING PERIAPICAL RADIOGRAPHS AGAINST CBCT**  
**INVESTIGATORS: MICHAEL DODD AND LES FEINBERG**

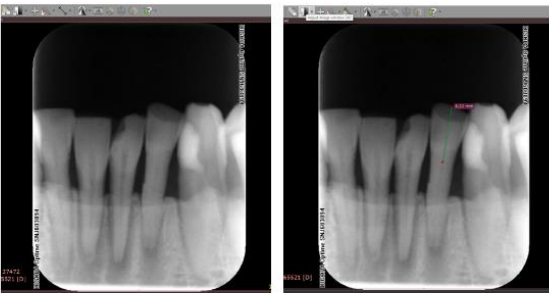
Thank you for participating in this study.

The task you will be asked to perform is as follows

- You will be presented with 45 radiographs, 30 of these will be periapical images, 15 will be CBCT images.
- On each image you will be asked to identify where on the image you first perceive the most coronal part of the root canal system in the I12.

**PA images**

- For the PA images you will be asked to measure this point to the midpoint of the top part of the incisal edge using the program measuring tool.

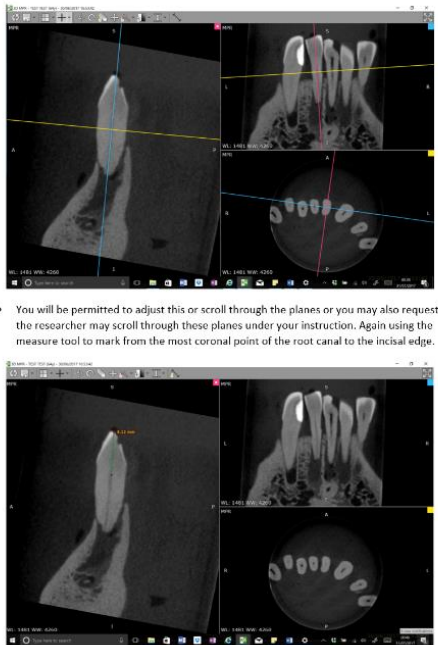


- In addition, you will be asked the following question:
  - How confident are you that this is the true location of the most coronal part of the root canal system?
  - You may give one of the following answers:
    - High confidence
    - Medium confidence
    - Low confidence

**CBCT images**

- With the CBCT images, the scans will be shown to you in sagittal, coronal and axial planes. These will be aligned in the following manner by the researchers:
  - Sagittal and coronal: along the long axis of the tooth
  - Axial: parallel to the incisal edge (SEE FIGURE BELOW)

1



- You will be permitted to adjust this or scroll through the planes or you may also request that the researcher may scroll through these planes under your instruction. Again using the measure tool to mark from the most coronal point of the root canal to the incisal edge.

- You will be asked to rate your confidence that this is the true location of the most coronal aspect of the root canal with the following three answers
  - High confidence
  - Medium confidence
  - Low confidence
- In addition you will be asked whether you believe the root canal to be continuous from the identified point to the apical terminus of the root canal system.

Figure -4-9. Calibration sheet given to observers explaining purpose of investigation and method for measuring incisal edge.

canal system or pulp chamber became visible.

The instructions also explained how the CBCT images would be presented with the images aligned in the long axis of the tooth in the sagittal and coronal views and in the mesio-distal midpoint on the axial view. Observers were told that they were free to manipulate the image as they required or could request the investigators to do this under their instruction. In a similar way to the PA the observers were showed how to measure from the incisal edge to the first point that the canal was seen, and they were recommended to use the sagittal image for this. If they identified the canal on another plane they could use the multiplanar reconstruction tooth (MPR) show this on the sagittal image which was then measured in the appropriate manner.

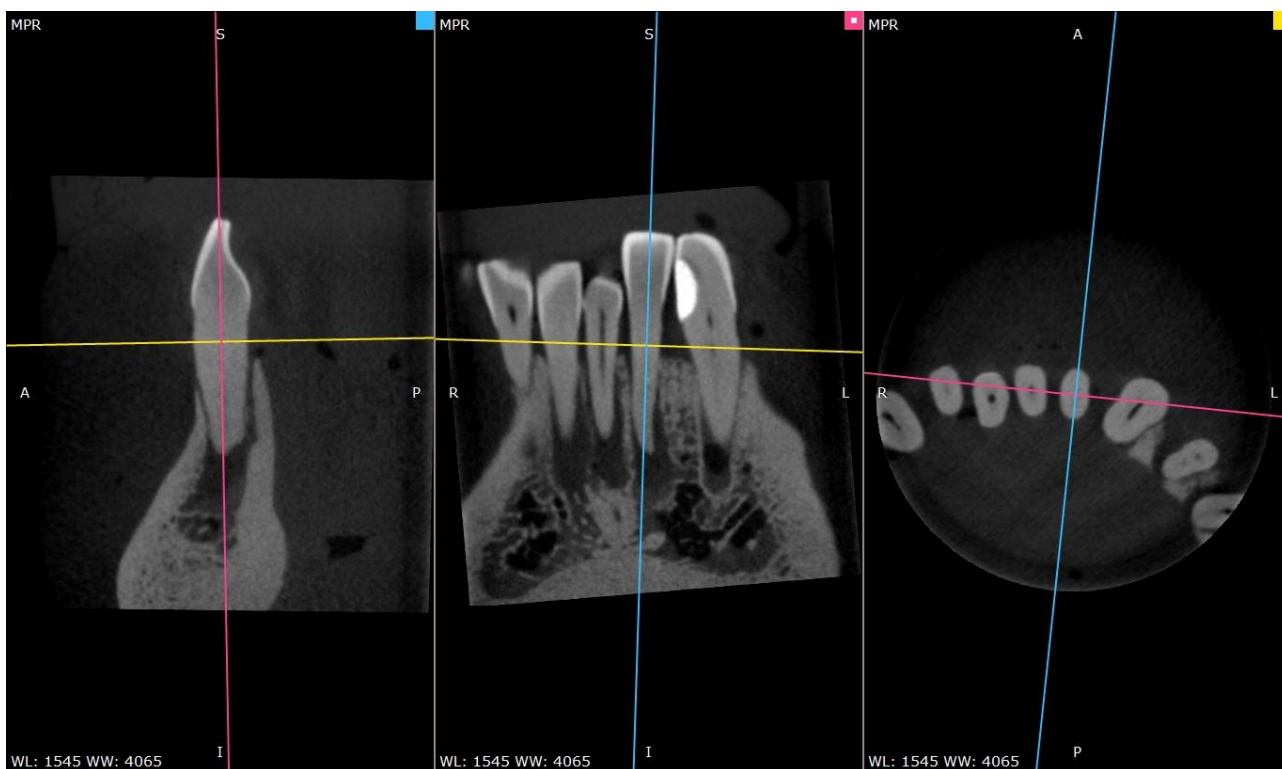


Figure 4-10 Alignment of CBCT images along the long axis of the tooth in the sagittal and coronal planes and through the mesio-distal mid-point in the axial plane.

### Statistical analysis

Data were given to a biostatistician at Liverpool Dental Hospital for statistical analysis. Interobserver agreement was calculated using intraclass correlation (ICC) for each individual image group. If any observers were outliers, they were removed from further statistical analysis.

To investigate differences between PA and CBCT, the mean distance from the mesio-distal and/or bucco-lingual midpoint of the incisal edge to first observed coronal pulp (IE-CP) value was calculated over observers (excluding one the outlier in the PA measurements). A pair sample t-test was then used to analyses if a difference existed between the two imaging modalities

#### Cross analysis of $\mu$ CT and Phantom study

Analysis of canal dimensions at PA and CBCT distances was performed using Mimics Mimic 20.0 (Materialise, Leuven, Belgium) The 3d model of the tooth was used to measure from the incisal edge to the average value for canal detection using CBCT and PA for each tooth. Using the centreline function within Mimics the best fit diameter, (DFit), the minimal diameter (DMin), maximal diameter (DMax) and cross-sectional area (CSA) were measured and recorded. Data were stored on Excel (Microsoft Corp, Redmond, Washington, United States) on a secure University of Liverpool computer. Statistical analysis was carried out using Microsoft Excel.

Chapter 4 A study comparing PA radiographs against CBCT images in the determination of the location of the root canal system

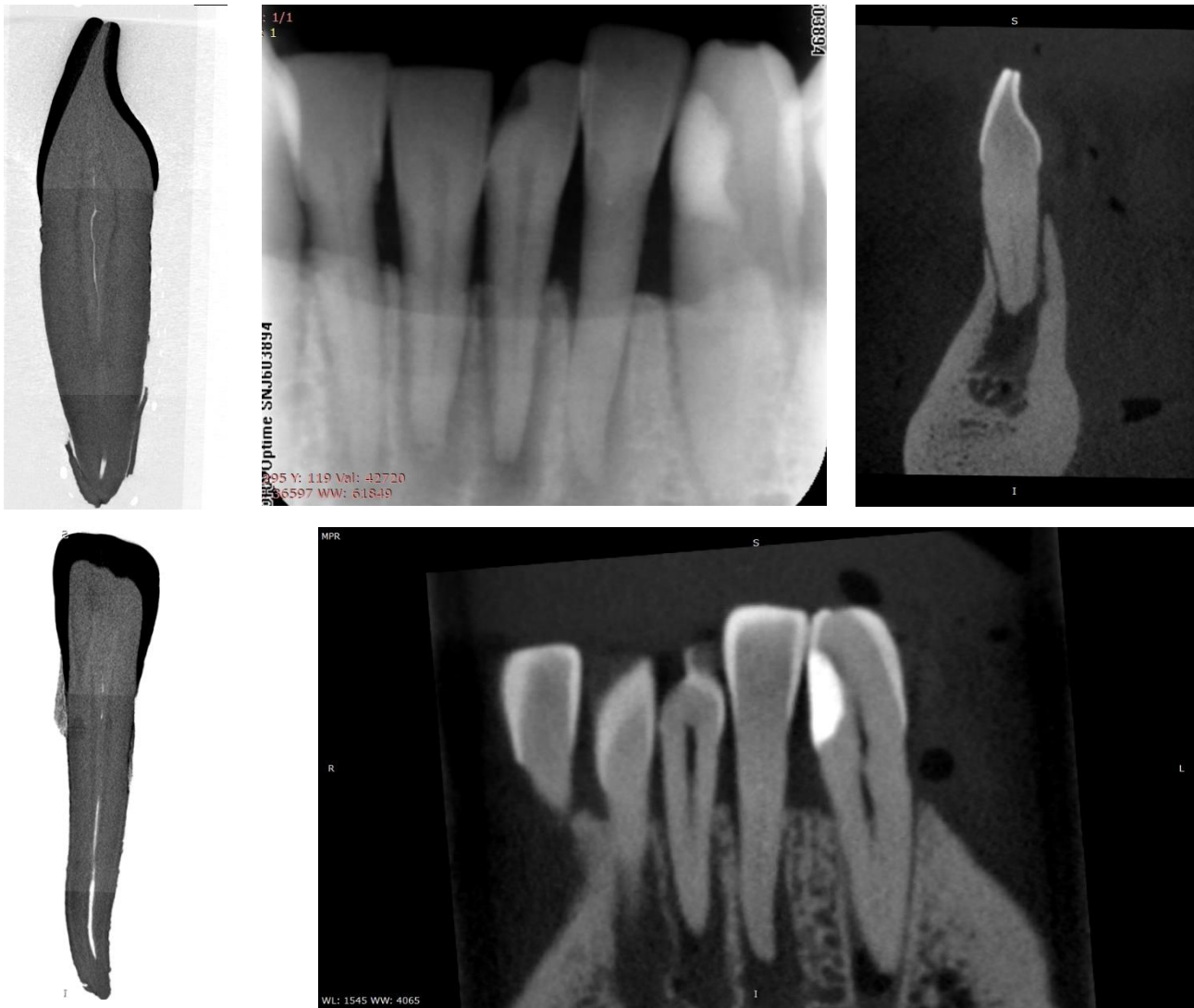


Figure 4-11. Typical images derived from phosphor plate images (top, middle) and CBCT (top right and bottom right).

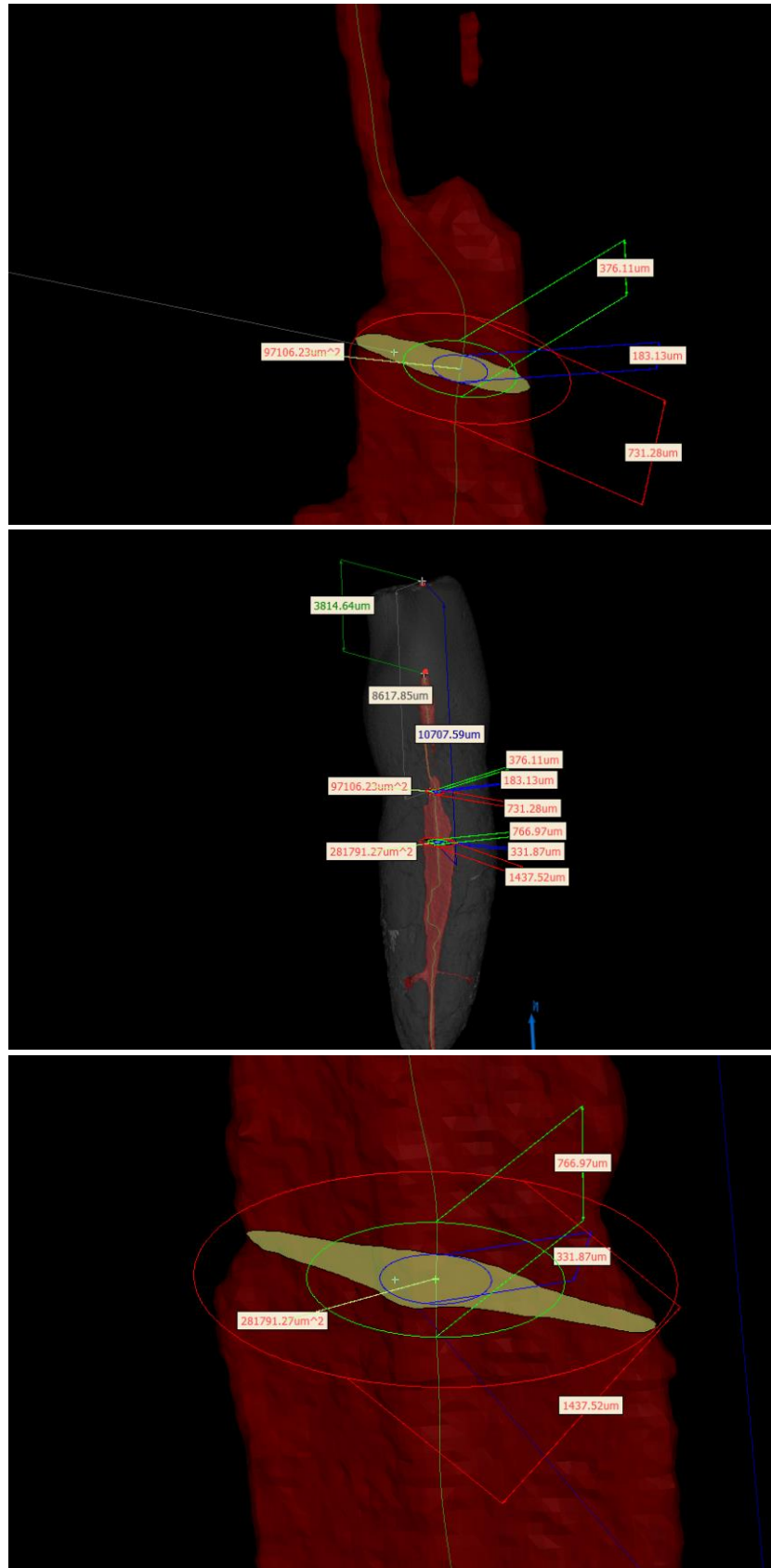


Figure 4-12. Analysis of the  $\mu\text{CT}$  canal dimensions at canal identification levels using CBCT and phosphor plates. Deriving the exact diameter is difficult since canals are not perfectly circular. In the above case the canal is particularly oval meaning that the maximal diameter (red), minimal diameter (blue) and best diameter may differ by more than 1000  $\mu\text{m}$ . In as such the use of cross sectional area (green shaded area) maybe more appropriate.

## Results

### Inter observer agreement

Overall agreement over canal location on the periapical images was moderate (ICC = 0.698). There was one outlier who had poor agreement with all other observers. This observer was excluded, and this increased ICC to 0.895. Agreement for canal location using CBCT was good with ICC of 0.849, for this group there were no major outliers.

### Canal detection on periapical radiography

In almost all cases observers identified the canal on CBCT images more coronally than they did using PA images.

The mean distance from the incisal edge to the first observed pulp space was 10.15 mm (SD = 3.94) in the PA group and 6.79 mm (SD = 2.38) in the CBCT. This was a mean difference of 3.36 mm between PA and CBCT groups (95% CI = 1.71, 5.02) and was statistically significant ( $p < 0.001$ , paired t-test)

	<b>μCT</b>	<b>PA 0°</b>	<b>PA 15°</b>	<b>CBCT</b>
1	8.62	18.96	17.83	12.05
2	7.30	11.26	8.81	7.88
3	3.86	6.22	5.68	4.98
4	5.71	8.17	8.66	6.83
5	4.56	5.11	5.26	4.46
6	7.49	10.47	14.67	8.10
7	7.60	8.96	13.12	10.28
8	2.50	10.99	7.56	3.79
9	-	12.97	10.46	6.65
10	8.58	10.70	10.78	8.68
11	3.81	5.06	4.30	3.81
12	7.95	9.76	8.90	7.20
13	4.34	8.60	7.94	4.82
14	3.72	10.35	12.40	5.26
15	-	8.39	8.70	7.06
Mean	5.85	9.73	9.67	6.79

Table 3-3. Distance from incisal edge to most coronal part of pulp. μCT values related to the first portion of continuous pulp

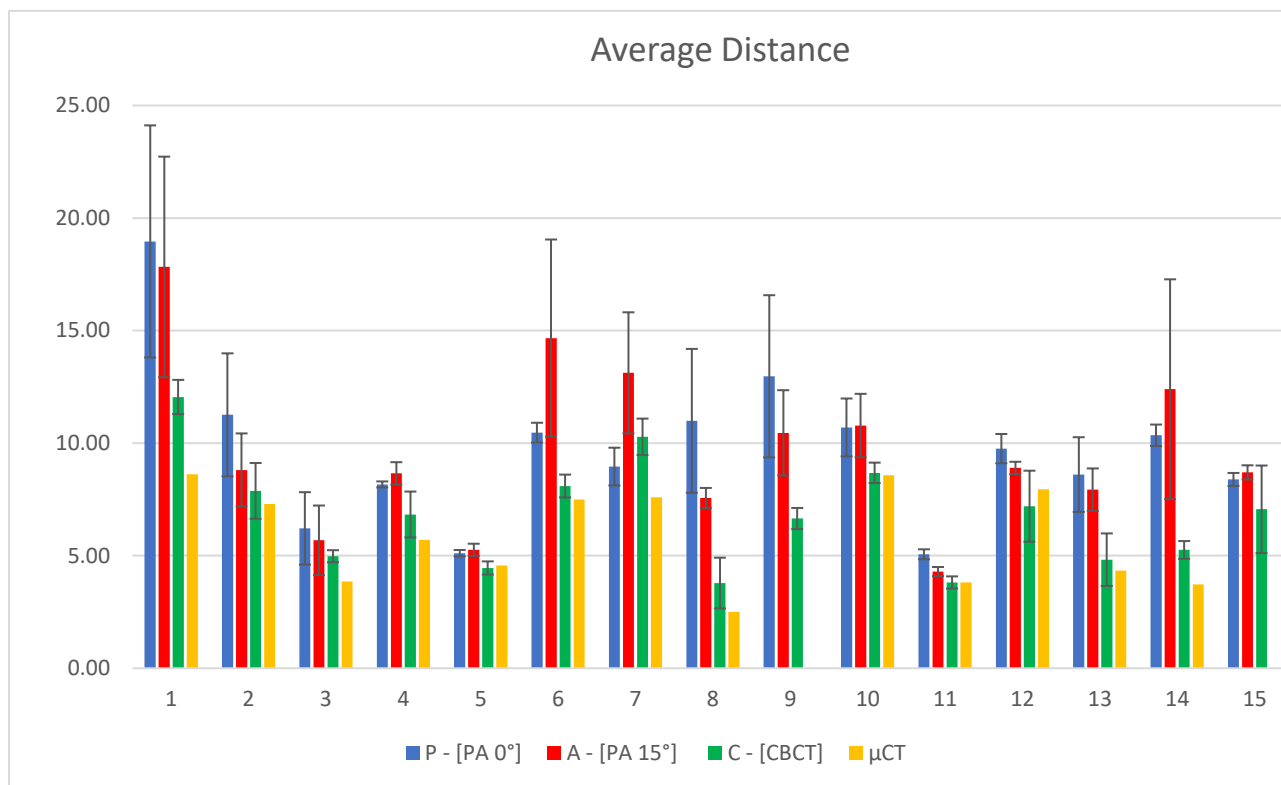


Figure 4-13. Comparison of the distance from incisal edge to first identified coronal pulp in 0° PA (blue), 15° PA (red), CBCT (green) and μCT (yellow).

#### Differences between μCT, PA and CBCT

Comparison with μCT measurements from the previous study show that μCT identifies the canal at a more coronal position than both CBCT ( $p=0.013$ , paired t-test) and PA ( $p<0.001$ , paired t-test). Mean distance for the canal detection on the μCT was 5.85 mm (SD = 2.06) which is a mean difference of 0.94 mm compared to CBCT and 4.3 mm in the PA group.

#### Correlation between canal diameter and detection on PA and CBCT

The mean diameter, as calculated from the μCT data, of canal detection in the CBCT group was 229 μm (SD = 119) and in the PA group it was 417 μm (SD = 206). This was a mean difference of 187 μm and was statistically significant ( $p= 0.0009$ , paired t-test).

When comparing the cross-sectional area of the canal at the respective identification points. Canals in the CBCT group had a mean diameter of 47743 μm<sup>2</sup> (SD = 41022) and in the PA group it was 123784 μm<sup>2</sup>.(SD = 127095) This is a statistically significant difference of 76041 μm<sup>2</sup> ( $p= 0.01534$ , paired t-test)



Tooth	CBID (mm)	Dfit (µm) (CB)	CSA (µm <sup>2</sup> ) (CB)	PAID (mm)	Dfit (µm) (PA)	CSA (µm <sup>2</sup> ) (PA)
1	12.1	139	14608	19.0	288	64692
2 <sup>‡</sup>	-	-	76172	-	-	120458
3	5.0	249	48451	6.2	319	73032
4	6.8	111	9375	8.2	263	53279
5	4.5	446	144382	5.1	773	470979
6 <sup>‡</sup>	-	-	22836	-	-	58967
7 <sup>‡</sup>	-	-	42997	-	-	29874
8	3.8	268	55612	11.0	422	112621
10*	8.7	131	12905	10.7	311	75319
11	3.8	376	97106	5.1	767	281791
12*	7.2	220	37133	9.8	276	59768
13	4.8	122	11342	8.6	330	84627
<b>Mean</b>	<b>6.3</b>	<b>229</b>	<b>47743</b>	<b>7.2</b>	<b>417</b>	<b>123784</b>

Table 3-4: Canal dimensions at identified levels using CBCT or PA imaging. CBID – mm from incisal edge that canal first pulpal space identified on CBCT image; DFit (CB) – best fit diameter of canal at CBID; CSA (CB) – cross sectional area of canal lumen at CBID. PAID - mm from incisal edge that canal first identified pulpal space on PA image; DFit (PA) – best fit diameter of canal at PAID; CSA (PA) – cross sectional area at PAID. \* canal was identified at a more coronal point on PA than µCT, the dimensions of the canal at the most coronal point on the µCT were used. ‡ 2 of more canal lumen at identification point. These were excluded to simplify comparison

## *Discussion*

### Construction of radiographic phantoms

A number of different materials have been described in the literature for construction of soft tissue phantoms such as acrylic, rubber and water. Mix-D has been recommended for having an anatomic number that is the same as water which is considered to be a good substitute for soft tissue. Water however is very difficult to contain in a way that replicates the contour and volume of soft tissue. MiX-D suffered from the problem of complex production and settling of the metal oxides that act as radiopacifiers. Polyurethane is inexpensive, simple to use and shows very similar attenuation to soft tissue. It can be added to and modified easily. The phantom constructed for the interpretation studies therefore acts as suitable design for future soft tissue phantom production.

The modular design of the phantom facilitates substitution of teeth with relative ease. This is important for studies in which multiple teeth are to be examined rather than a constant structure for studies involving dosimetry or for quality assurance purposes. The phantom design serves as a template for further studies in which CBCT and periapical radiology can be compared.

The Hounsfield values derived from the medical CT validate the phantom in terms of its similarity to soft tissue and can therefore be expected to attenuate the x-beam in a similar way to that of real tissue.

### Possible studies using the phantom

Whilst the phantom described has been developed to study radiographic interpretation of CBCT and PA views of calcified root canals there are number of other potential studies that it could be employed for.

The phantom could be used to study the various exposure setting of a CBCT machine in the detection of root canals, root fractures or simulated resorption defects.

It could also be used for comparing different makes or models of CBCT scanners in terms of detecting the anatomical features described above or investigating resolution, image quality or artefacts. An interesting study would be to take a tooth with particularly fine root canal system and

scan it within the phantom in various makes of CBCT machine. A number of observers could then be asked to determine the location of the canal start or the root canal configuration. Such a study would determine the true ability of various machines to detect such structures against a set standard. Given manufacturers' claims for their device often rest upon theoretical resolutions, a measure of a machine's real world performance would be of great value to practicing clinicians.

### Limitations of the phantom

The designed phantom is limited to investigation of radiography of the mandible. Many of the endodontic interpretation studies have focused on the MB root of the maxillary first molar. The maxilla as a whole presents a more complex anatomy that is likely to have an effect on image quality. Anteriorly the nares, anterior nasal spine and incisive canal and posteriorly the zygomatic buttress and maxillary antrum are known to complicate image interpretation. Consequently, construction of a maxilla phantom would require a section of the skull base and facial skeleton as well as the maxilla itself. However, the phantom described in this study demonstrates the validity of the soft tissue base and application of the above method would likely result in a similarly realistic phantom.

The phantom did not include a section of cervical vertebrae. In CBCT image it is likely that such a structure would have an effect on beam attenuation but to what degree is unclear. A modification to the design would be to incorporate this feature to emulate even more closely the *in vivo* situation.

### Canal identification, canal depth and human error

A number of recent articles have presented technological advancements in the use of CBCT as a guide to manage calcified canals. Either by providing additional information to assist the clinician to locate the canals or using the information to fabricate a stent that will orientate the bur in the correct alignment and to the correct depth.

However, despite the excitement of managing the clinical problem via such technological advancements the question must be asked as to whether such sophisticated methods are actually necessary. If CBCT alone can be used to identify the canal and allow the dentist to prepare the

access to the correct depth, then it may be possible to dispense with expensive accoutrements such as stents.

Identification of the canal more coronally also means that the risk of perforation is reduced. This can be shown theoretically using simple geometry:

$$c = 2r \sin \frac{\alpha}{2}$$

Where  $r$  is the depth of the access cavity,  $\alpha$  is the angle of error during the access from incisal edge to canal orifice and  $c$  is the distance between the two sides of the canal orifice. If we assume that operator error in angulating the bur is around  $5^\circ$  either side of the canal orifice then an access cavity of 10.15 mm maybe  $\pm 0.89$  mm from the canal orifice, whereas if access cavity depth is 6.79 mm the distance would be  $\pm 0.59$  mm. Although this does not seem like a large difference the problem is compounded by the taper of the root, which naturally decreases as it approaches the apex. In other words, the error of the access cavity increases with depth with less space in which to make an error.

### Major findings

this study has identified the superiority of CBCT over PA imaging in determining a more accurate depth of the canal from the incisal edge. Thus, the null hypothesis that there is no difference between the two modalities must be rejected. The null hypothesis that there is no difference between the canal dimensions at the levels detected by CBCT and PA must also be rejected.

### Comparing CBCT and PA imaging in calcified teeth

Despite exhaustive searches, no previous study has investigated CBCT's ability to detect calcified canals over PA in a quantitative way. This study demonstrates CBCT has the ability to detect canals of both smaller diameter and smaller cross-sectional area than phosphor plate images.

### Comparison with other studies

CBCT has been investigated for its ability to detect canals, particularly the mesiobuccal root of the maxillary first molar. These studies have shown CBCT is an effective method for canal detection. The MB root of the maxillary molar does have some similarities with lower incisors. The root is broad

in the bucco-lingual (palatal) direction like mandibular incisors as well as the common occurrence of two canals. However, whilst some inferences can be drawn from this the surrounding structures such as cortical bone are quite different and therefore the ability of CBCT to detect canals specifically in mandibular incisors is warranted.

Comparison with other studies that attempt to detect fine structures such as cracks is also worth consideration (Patel et al, 2013; Brady et al 2014). Brady et al (2014) investigated CBCT and PA in their abilities to detect vertical fractures and found CBCT to be superior. In their study the width of cracks varied from 30 to 110  $\mu\text{m}$ . Interestingly some cracks of less than 50  $\mu\text{m}$  were detected. although with lower sensitivity than larger cracks (>50  $\mu\text{m}$ ). This might be considered impossible given the Shannon-Nyquist theorem. However, cracks differ from canals because, although narrow in one dimension, they will be much broader in another plane.

Relating the canal dimensions derived from  $\mu\text{CT}$  to the CBCT and PA data is complex. Firstly, two samples could not be analysed due to missing  $\mu\text{CT}$  data and two values for the distance from the pulp to the incisal edge (CP-IE) in the CBCT group were smaller than the  $\mu\text{CT}$  value! In the latter cases the canal diameters at the very start of the canal were used but it is possible that observers had detected a small pulpal coronal to this point as in both these teeth multiple, small isolated pulpal spaces were observed more coronally in four cases the axial section showed two canals at the point of identification which complicates the ability to draw conclusions on detectable diameter with either modality. Use the cross-sectional area allows the total of canal at the ID point to be calculated as the values from each canal branch can be combined. The root diameter may also be a determinant that was not investigated in this study.

### Optimization of CBCT

CBCT exposure requires optimisation to balance dose reduction according to the ALARP principle but also extracting the maximum diagnostic yield from the images. In cases requiring the identification of the canal system it would seem logical that high resolution images are of particular importance. Smaller field of views images can achieve higher resolutions as a smaller area is being projected over the detector and given that CBCT imaging for endodontics usually has a small area

of interest this should be the standard. However, resolution is not the sole factor involved in canal discrimination. Contrast is also extremely important. A high contrast ratio between an empty canal and the surrounding tooth structure mean that the reconstruction algorithm will register the area as empty. Lower the kV has the effect of improving contrast but simultaneously increases the noise to signal ratio. Thus, detection in terms of CBCT setting is a balance between spatial resolution, contrast and noise.

### *What are the canal dimension of extensively calcified teeth?*

There are no exact dimensional definitions for canal calcification (or pulp obliteration or sclerosis). Indeed, complete calcification is often perceived rather than actual as illustrated by the  $\mu$ CT study. It appears that canals do not tend to recede from the CEJ as much as narrow in diameter. This is clinically important since this may mean deep access cavities are unnecessary but rather an anatomically informed approach should be employed that utilises a centred access with instruments that are conducive to cannulation of the canal lumen (Clark and Khademi, 2009).

### The dimensions of canals and their detection using different imaging modalities

The minimal detectable canal diameter does not appear to be the same as the minimum voxel resolution of 80  $\mu$ m as claimed by the scanner Morita (2017).

There are a number of studies investigating canal detection, particularly the presence of the MB2 canal in the first maxillary molar. However, none of these studies has actually tried to relate the dimensions of these canals to the likelihood of detection using CBCT or periapical radiographs.

### What are the limitations of CBCT in detecting root canal anatomy?

#### Anatomical factors

It is implicitly obvious that larger diameter canals will be more readily detectable on CBCT images. However, stating a minimum canal diameter that is detectable is simplistic due to confounding factors with the bone and root morphology, canal configuration, the scanner itself, the exposure settings, artefacts from surrounding structures and movement as well as observer factors.

It would nevertheless appear that within the limitations of the study deductions can be drawn on the limits of canal dimensions detectable. The mean best fit canal diameter detected CBCT was 229  $\mu\text{m}$  and with phosphor plate it was 417 giving a mean difference of 187  $\mu\text{m}$  was found between canals identified with CBCT and those using phosphor plates. This is in line with theoretical limitations proposed by the Shannon-Nyquist theorem as the minimal resolution of the Accitomo 170 is 80  $\mu\text{m}$ , meaning that a structure of 160  $\mu\text{m}$  should be detectable on the CBCT image. Four images had best diameters lower than this limit, but this may be explained by the fact that canals are rarely perfectly circular. When the maximal diameters of the canals were compared to this best fit value, three canals showed maximal diameters around or above 160  $\mu\text{m}$ .

Clinically such a difference is significant as the more coronal aspects of the canal demonstrated an inverse taper effect. Consequently, CBCT appears to detect the canal at a more coronal level. Given that this difference represents an instrument difference of over three file sizes it may inform the clinician that selection of an access and shaping strategy that would minimise iatrogenic events.

However, with the case of more than one canal, it may be useful to consider the ratio of dentine to canal space as the influential factors. It would be reasonable to assume with conventional PA that the bucco-lingual dimension of the canal would be more of an influence given that this the direction of the beam is perpendicular to the incisal edge.

With CBCT however, given that the scan is three dimensional it may be that the cross-sectional area of the canal maybe be more influential. The grey value of a CBCT voxel is determined by the reconstruction algorithm combining information of each individual projection. Therefore, as each projection is a different angle to the last, orientation of the tooth is unlikely to be important. In this study the cross-sectional area of the canal was smaller at the first point of detection using CBCT than it was using phosphor plate imaging.

An additional factor to consider is the canal content as this will affect the contrast between the surrounding dentine and the canal. Unfortunately, without correlating the  $\mu\text{CT}$  to histological sections it is impossible to ascertain the content of the canal. Furthermore, lower incisors often have complex

canal configurations. Such complexity is likely to make interpretation of root canal systems on both CBCT and PA images more difficult and this is a potential confounder within the study.

### Observer factors

Whilst technical considerations are certainly important it is the observer that *detects* canals on the image. Varying exposure parameters may influence the likelihood of observer detection, but some variation will be attributable to observer experience in interpretation of CBCT, experience within the speciality of endodontics as well as effects of fatigue of looking repeatedly at images. Other dental disciplines have shown significant differences in perception of colour change (Alghazali *et al*, 2012) and it is reasonable to assume such differences will also be seen which perception of differences of the greyscales of radiographs.

### *Maximising canal detection rates with conventional periapical radiographs*

Digital radiographs can be acquired by either using a film-based system or a digital based system. Digital systems are categorised as either direct digital using a sensory or semi-direct using a phosphor plate system. Conventional film has been shown to produce a resolution of 20 LP/mm or greater. Whilst manufacturers of digital systems claim anything up to 33 LP/mm studies have shown that the actual resolution is much lower and usually lower than conventional film ranging from 8-15 lp/mm. These findings are important when selecting a system that will maximise canal detection.

The question arises as to which is more important in conventional radiography – spatial resolution or contrast resolution. The answer to this question is complicated by factors such as the relative contrast of the canal contents and surrounding anatomical structures. If the canal contains fluid the contrast will be lower and therefore more difficult to detect than a canal filled with air. Likewise, surrounding anatomical structures of similar radiodensity may produce anatomical noise which makes subsequent interpretation more difficult (Patel *et al*, 2016).

### *Implications for clinical practice*

Access to the root canal system requires careful planning. Knowing the depth at which the canal will be detected provides the clinician with the information to perform predictable access. If the canal is



not located at the depth the clinician still knows that the canal is at this level but needs to look lateral to the initial entry point. Such knowledge simplifies the access procedure and consequently reduces the time required for treatment.

A number of authors have investigated the use of 3D guides for endodontic access. These are particularly useful in cases of pulp canal obliteration where location of the root canal system is difficult. Consequently, such guides promised reduced treatment time AND reduction in dentine removal. Initial investigations have shown promise in terms of accuracy and reliability (Connert et al, 2017)

This research dovetails with that of 3D planned guides by providing the requisite information to determine the correct drilling depth. Although it could be argued that the end target is the apex of the tooth, there are instances where this is not possible due to root curvature. Consequently, canal identification still provides important information for endodontic access

## *Future studies*

A major component of image degradation is the presence of artefacts. As discussed previously artefacts can be attributed to a number of sources. Particularly relevant artefacts for calcified canals may be the presence of movement. As calcification can be associated with the ageing process which corresponds with an increased incidence of movement disorders such as Parkinson's disease, but severe calcification after trauma (pulp canal obliteration) is seen mainly in the young patient who may struggle to keep still. Motion artefacts are known to degrade image quality. However, this may be noticed only when significant amounts of movement have occurred. In reality, every patient may move a small amount, and this may not be obvious on a cursory examination of the image. Additionally, calcification of the root canal space may be associated with a heavily restored dentition (Abou-Rass, 1982).

### Effects of movement artefacts and optimisation of image when movement has occurred during scanning

Spin-Neto et al (2013) used a robot to simulate motion artefacts and assess the impact of image quality on structures such as the mental foramen. A similar rig could be used to investigate the effect of movement on canal detection. The robot set up described by Spin-Neto et al (2013) could be replicated and programmed with motion capture data from recorded patient movement.

The scans could then be interpreted in a similar way to the canal identification study described using both 180° or 360° reconstructions. Such a study would further improve the understanding of the limitations of CBCT in canal identification and perhaps inform methods of limiting or minimising patient movement during scanning in order to maximise diagnostic yield.

## Determining the effect on canal detection with artefacts caused by different restorative materials

To assess the effect of surrounding restorative materials upon the ability of CBCT to detect canals, the mandible used in the previous study or perhaps a model simulating a mandible could be produced which would allow interchangeable tooth inserts to allow simulation of various configurations of surrounding teeth including roots, posts, root fillings, GP and silver points.

A previously scanned tooth that has already been analysed with  $\mu$ CT and shows a reduced but discernible root canal would then be placed in the model with placement of surrounding teeth with various restorative materials such as a root canal filling, metal post and a fibre post. The scans could then be interpreted by a given number of observers to see the effect of various restorative materials on canal detection. In this way recommendation for the use of CBCT could be developed to inform the clinician when the diagnostic yield is low due to the level of artefacts created and therefore not justifiable.

## Improving canal detection with the use of a contrast medium.

CBCT has poor contrast resolution and this will have an impact upon the observer's ability to discriminate between minor changes in radiodensity. The use contrast medium to improve canal detection has been used before (Hasselgren and Strömberg 1976, Naoum et al, 2003) but it has not been used to detect aid canal detection on CBCT. It is likely an ideal contrast medium would be more radiopaque but not so much that it introduced artefacts such as beam hardening which could possibly reduce canal detection. Challenges to such a method could be the technical hurdles required to produce sufficient pressure within the access cavity to introduce the medium into an extremely small lumen. However, given the possible advantages of improved contrast the technique warrants further investigation.

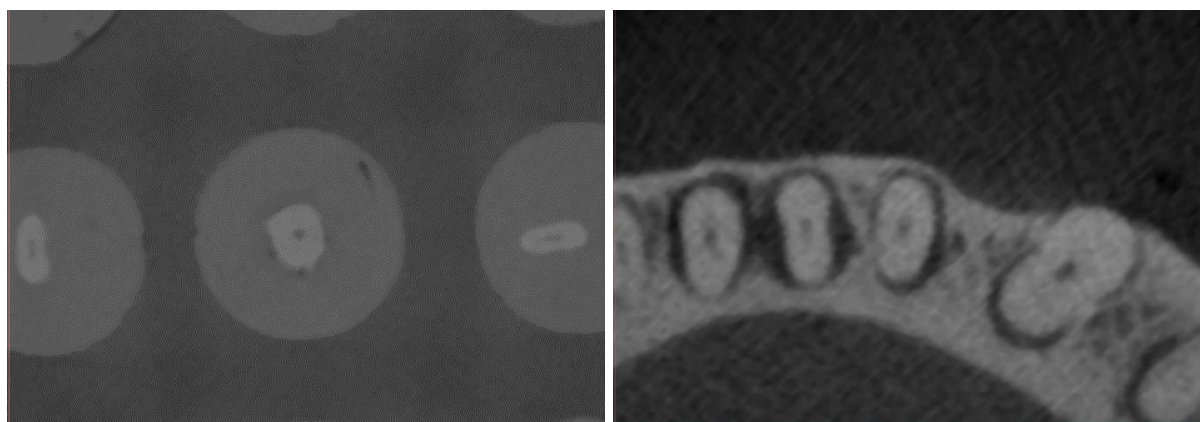
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## Chapter 5 - Summary and Future Directions of Research

The limited literature on the calcified canals is a hindrance to further improving the clinical management of this problem. These studies have attempted to address some of the gaps in the existing knowledge with a in depth study of the morphology of calcified canals

### Importance of a realistic phantom

It would appear that previous studies on the use of CBCT in identification of root canal anatomy have used inadequate methods to emulate the effect of soft tissue upon the image. The machine used for this study, the Accuitomo 170, has one of the best specifications on the market but comparison of clinical images produced by it to some of those generated by previous studies would suggest an unrealistic signal to noise ratio. Such clarity would like to overestimate the ability of these devices in detecting fine structures (as illustrated in fig 5-1). As such the value of using CBCT to detect such anatomy may be misrepresented leading to its overuse by clinicians. The phantom described demonstrates the validity of an inexpensive material, polyurethane, as a soft tissue substitute to delivery images that are clinically realistic. The use of more complex soft tissue substitutes such as Mix-D (Jones and Raine, 1949; Brand et al, 1989) would therefore appear to be an unnecessary complication. Polyurethane can be cast easily to any shape, it can be modified with rotary tools and added to easily. These benefits recommend it, along with similar beam attenuation properties to soft tissue, as an excellent choice in future maxillofacial phantom designs.



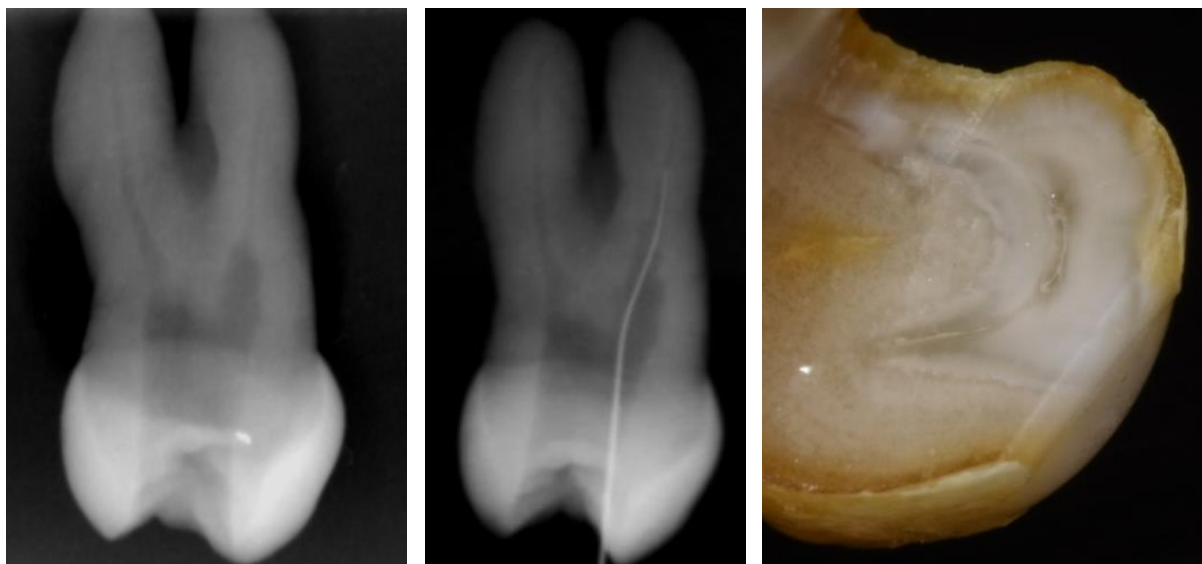
*Figure 5-1. Comparison of teeth scanned mounted in putty in acrylic well (left) compared to teeth mounted in real bone with polyurethane soft tissue analogue (right). Note the 'clean' scan on the tooth without surrounding analogue leading to unrealistic images.*

Some limitations of the phantom involve the use of a real mandible. To give a realistic appearance this must be soaked thoroughly to ensure the trabecular space is filled with water making storage more difficult. To place teeth within edentulous regions requires modification by burs to create or modify existing sockets and consequently it is difficult to create a very close adaptation to the tooth surface. Whether this is of any relevance to the resulting image is unclear, but it may be useful in studies trying to simulate periapical periodontitis. The construction of a realistic bone analogue would help overcome these limitations but would be much more difficult due to bone having a much more complex, reticular pattern of hard tissue interspersed with connective tissue spaces. One possible solution would be to 3D print such a complex structure using a material with sufficient radiopacity to mimic the mineralised content. Inzana et al (2014) studied the use of a calcium phosphate material printed to use as a bone scaffold. Whilst this was not printed to resemble mature bone it may be possible to adapt the technique to print such a structure. Whilst this would allow realistic bone phantoms to be created to fit perfectly around any tooth the drawbacks are the expense of production and the need for sophisticated software and hardware. As 3D printing technology continues to advance at a rapid rate it is likely that the accessibility and cost of producing increasingly realistic phantoms will become more attractive.

#### **Importance of more detailed anatomical data on calcified canal**

Extensive morphometric analysis of the canal has not previously been available, and it is hoped that a deeper understanding of the anatomy will further inform technical innovation to access and negotiate the root canal system in a predictable manner whilst maximising preservation of radicular dentine and minimising treatment time. The micro CT study presented does support some basic assumptions that have previously been presented in the literature. Firstly, for most of the root length a canal is present, thus it seems 'total obliteration' of the root canal is highly unlikely or it is too infrequent to be detected by the study sample size.

Whilst  $\mu$ CT can exclude areas of mineralisation, the exact contents of the canal is unclear as many types of soft tissue will share a similar relatively radiolucent appearance. Fig 6-2 shows an example of a radiolucent canal that was negotiable due to a clear substance deposited within the lumen. Consequently, the need for histological studies that correlate the  $\mu$ CT with confirmation of the exact



*Figure 5-2. Extracted tooth being used in undergraduate endodontic course. The undergraduate was unable to negotiate to the terminus of the root canal despite the radiographic appearance of a lumen. Sectioning the root in the apical third demonstrates the presence of a canal but filled with an unknown clear substance that prevented negotiation. This material could be speculated to be unmineralised collagen or hyaline but this would need to be verified histologically.*

content of the lumen is needed. The samples used in this study would be not be ideal for histological study due to the storage within a disinfectant (Gigasept) rather than a histopathology fixative. Furthermore, the history of teeth used is unknown and therefore the process of calcification is unclear. Aetiology could include slower secondary dentine formation that may produce more uniform canals or rapid pathological mineralisation resulting from trauma. A future study addressing these details would be useful although likely to be difficult to obtain sufficient samples.

Importance of understanding the possibilities and limitations of CBCT in the clinical management of calcified canals.

As use of CBCT becomes more widespread the justifications for its use must rest on a sound scientific base. However, commercial pressures to overemphasize the abilities of the hardware coupled with overly enthusiastic adopters can often leave the scientific base lagging behind. Undoubtedly CBCT will play an ever-increasing role in virtually all dental specialities and such adoption will certainly result in the technology being driven forward to reduce dosages and improve image formation. One area that is likely to bring such changes is the use of iterative reconstruction. In this method, the algorithm effectively compares the data against an initial estimate of what the image should look like. This is then used a second guess which is again compared to the image data and so on. Given enough time and processing power a perfect representation of the image can be

produced. As processing power and the sophistication of the algorithms improves this will allow the production of images with minimal artefacts and high resolution.

Presently, CBCT seems capable of detecting canals more coronally than conventional phosphor plate radiographs. Some element of caution must be taken when drawing inferences from these data. The variation in film, sensor or phosphor plates has not been determined and it is possible that traditional 'wet' film or CCD sensors may prove to be superior. Nevertheless, CBCT does appear to have a role in the management of calcified canals. An interesting question arises over whether an CBCT image taken before access is better than one taken after a failed access cavity. In the former, this may potentially lead to more conservative access whereas taking one after a failed attempt to locate the canal may already render the root weakened as the clinician removed ever increasing amounts of dentine in an attempt to locate the canal. Conversely taking a CBCT when the canal cannot be located may make it easier for the clinician to orientate to the canal space whilst taking a CBCT prior to access still requires get skill for the dentist to transfer the information from the scan to visualise the internal anatomy of the tooth in three dimensions. The  $\mu$ CT study demonstrates the presence of a canal at or below the CEJ in most cases, the canal being located close to centroid of the cross section of the root. Therefore, it may be prudent for the clinician to access the tooth in a conservative way and based on these dimensions as it may be possible to locate the canal based on this anatomical knowledge. If the canal cannot be located after this a CBCT should be considered. As shown previously, drilling deeper risks excessive removal of dentine or perforation, rather than drilling blindly the CBCT could help re-orientate or perhaps allow the fabrication of printed polymer guide if the canal appears to be particularly deep. A cost-benefit analysis of either situation would be useful, considering radiographic exposure against iatrogenic damage, clinical time spend, and economic costing would possible.

Although great efforts have been made to replicate the clinical reality of CBCT imaging of teeth there is likely some limitations that are inevitable with In vitro studies. As mentioned in the previous chapter, the effect of movement will likely have a detrimental effect on the image and future studies controlling for this would be worthwhile.



Additionally, some limitations exist with calculating the minimal detection diameter of canals when using either CBCT or phosphor plates. Firstly, the canal does not have a perfectly round shape, so calculation of the diameter can be very difficult, particularly in very oval canals. Secondly, it is likely that some magnification in CBCT and PA images meaning that the distance measured on the PA and CBCT does not exactly correlate to the  $\mu$ CT image. Furthermore, there will be some errors transposing the measurement to the  $\mu$ CT even if the dimensions were the same. It can be seen from the  $\mu$ CT study that canal diameter can change significantly within only a few  $\mu$ m, therefore small errors in measurement will give very different results.

Thirdly, CBCT and PA images results only applicable to Accuimoto 170 machine and the Digora system respectively using a unique sample set. A way to compare various machine could be aided by the construction of standardized canal phantom with specific canal diameters within a dentine analogue. These 'canals' could be made by using wire of specific diameter placed in the analogue material being poured or perhaps if the material selected was already solid, the use of a laser to create channels of specific diameter could be considered.

## *Suggestions for further studies*

### Studies to determine the contents of calcified canals

#### *Histology*

Various tissue types have been described in the literature some tissue occupying the root canal space appear more like bone or fibrous tissue and potentially this could result in differences in the radiodensity on CBCT. Histology could be complementary to the present study by measuring the diameter of the calcific tissue rather than the canal lumen. This could then be combined with other information such as canal lumen diameter to investigate the effect of tissue type on canal detection rates

#### *Radiodensity investigations using hydroxyapatite phantoms for bone and dentine*

Another method to help determine the type of tissue obliterating the root canal space is the use of a radiodensity phantom. As bone and dentine have different amounts of hydroxyapatite it is possible to create acrylic blocks with different proportions of hydroxyapatite within them. This could then be calibrated with known tissue types of bone and dentine.  $\mu$ CT scans could then be examined in the area of the obliterated lumen and the radiodensity calculated. This would then provide information on the probable tissue type within the canal.

#### *Calcified canal phantom*

Abstraction of canal morphology could be used as a baseline test in various machine. Fine wires of know dimension. 80, 100, 120, 140, 160  $\mu$ m could be used in produce canals in cast tooth models of a dentine substitute which would then be implanted within a phantom as previously described. This would then allow comparison of various scanners on the market and determine which shows the greatest sensitivity in detection of these fine structures and therefore which is most suitable for producing images in the management of calcified teeth.

## Studies to investigate the relative efficacy of proposed treatment methods and instruments for calcified canals

### *Hydration and colour shift*

The use of dental microscope in endodontic access has provided a whole new level in the visual cues when locating the canals. Colour difference in the pulp floor are well recognised as a method to locate canals but the differences in colour are related to the relative hydration of the root canal system. When the pulp chamber is dried, differences between different shades of dentine are more difficult to detect. Conversely, an overly wet chamber obscures details of the chamber floor. When moistened the dentine seems to show a greater contrast between grey dentine shades of the pulpal floor and the more opaque, white shades of secondary dentine.

Thin section sections from areas of the root with reduced canals spaces could be photographed under varying degrees of hydration to determine the greatest level of contrast. This would provide clinical useful information about the optimal level of moisture to use to maximise the detection rate of sclerosed canals.

### Pathfinder files and Non-Instrumentable canals

One of the clinical challenges treating calcified canals is negotiating to the canal terminus. Molven (1973) found good agreement between the visibility of canals on a radiograph and difficulty instrumenting them. As calcified canals are unique an in vitro method of comparing instruments specifically manufactured for this purpose is difficult. Allen et al (2007) compared the efficient of pathfinder files using standard acrylic blocks. However, these blocks do not have realistic anatomy to make useful inferences about the files relative effectiveness in calcified canals.



Figure 5-3. Conical EndoGuide burs which are claimed to be more conducive to canal location.

Using the  $\mu$ CT data, canals could be printed out of polymer to match the anatomy. These teeth could then be used to attempt negotiation. Although current printing technology is limited to diameters of  $> 100 \mu\text{m}$ , rapid advances in this field will likely mean that printing of extremely fine structures will soon be possible.

### Evaluation of bur design on endodontic access of calcified canals.

Opinion on ideal access cavities varies but a common recommendation for endodontic access is with the use of the round bur. Clark and Khademi (2009) have argued that the way we are accessing these teeth that is wrong and that much of this can be attributed to the use of round burs and the angle at which access is commenced.

In a series of articles Clark and Khademi (2009a, 2009b, 2010a, 2010b) claim that the use of round burs and squared end burs are both unnecessarily destructive but also an impediment to locating canal. Round burs they state are responsible for gouging access cavities whilst conical burs have a centring action once the tip of the bur enters the lumen of the canal. Furthermore, they claim that conical burs create a flat access wall, which even if off axis, aids canal location as the tip of the endodontic file slides down this surface. Conversely, the rounded surface created by ball ended diamonds will tend to deflect endodontic files from the canal orifice.

Although some of their assertions seem logical, the basis of their claims is effectively unproven. Additionally, both authors have a financial interest in the alternative products that they recommend. Whilst this does not necessarily mean they are wrong, further independent study is necessary to test the validity of their claims.

It would be interesting to study the effect of bur shape and angle of access upon the ability to localise a small canal. 3D printed teeth using the anatomical data of this study could be manufactured to give an array of different teeth with varying canal diameters at the initial pulp space. Teeth could be then divided into one of four groups, one group using traditional access from the cingulum and using round burs, the second with an incisal access design but again using round burs, the last two groups would be the same as the first two but using conical EndoGuide burs. This would then allow the relative advantages of bur design over access design to be evaluated.

### CBCT for access

Whilst evidence to support the use of endodontic guides is available. An assumption has been made that such devices are necessary. A study to investigate the difference between CBCT *aided* access and CBCT *guided* access is necessary to further justify the increase in complexity. A study could be designed in which teeth previously scanned with both  $\mu$ CT and CBCT could be standardised and printed and divided into two groups. The first group would be given the radiographic information and instructed to access the teeth without a guide; the second would be provided with a printed guide similar to those outlined in previous studies (Connert et al, 2017). This study would help explore the question of whether the additional three-dimensional information given by CT is sufficient by itself or if guides provide significant clinical advantages.

## Conclusions

The study of calcified canal is a under explored topic that is fertile ground for further research. The clinical frustrations of managing these teeth supports the value of further studies. It is clear that to address these issues fully, developments in the understanding of the aetiology, pathogenesis and histology of such teeth needs improvement which in turn could guide further research and development of more conservative and more efficient clinical techniques. The role of CBCT will almost certainly play an ever-increasing role in this and as such imaging technology improves so must research keep up to validate or temper the claims of commercial sector.

## Acknowledgements

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Finally, I would like to thank my supervisors Professor Jarad and Professor Youngson for overseeing this work and helping me through the many pitfalls and struggles I encountered on the journey.

## Appendix



# AAE Endodontic Case Difficulty Assessment Form and Guidelines

### PATIENT INFORMATION

Name \_\_\_\_\_

Address \_\_\_\_\_

City/State/Zip \_\_\_\_\_

Phone \_\_\_\_\_

### DISPOSITION

Treat in Office: Yes  No

Refer Patient to:

\_\_\_\_\_

Date: \_\_\_\_\_

---

## Guidelines for Using the AAE Endodontic Case Difficulty Assessment Form

The AAE designed the Endodontic Case Difficulty Assessment Form for use in endodontic curricula. The Assessment Form makes case selection more efficient, more consistent and easier to document. Dentists may also choose to use the Assessment Form to help with referral decision making and record keeping.

Conditions listed in this form should be considered potential risk factors that may complicate treatment and adversely affect the outcome. Levels of difficulty are sets of conditions that may not be controllable by the dentist. Risk factors can influence the ability to provide care at a consistently predictable level and impact the appropriate provision of care and quality assurance.

The Assessment Form enables a practitioner to assign a level of difficulty to a particular case.

### LEVELS OF DIFFICULTY

**MINIMAL DIFFICULTY** Preoperative condition indicates routine complexity (uncomplicated). These types of cases would exhibit only those factors listed in the MINIMAL DIFFICULTY category. Achieving a predictable treatment outcome should be attainable by a competent practitioner with limited experience.

**MODERATE DIFFICULTY** Preoperative condition is complicated, exhibiting one or more patient or treatment factors listed in the MODERATE DIFFICULTY category. Achieving a predictable treatment outcome will be challenging for a competent, experienced practitioner.

**HIGH DIFFICULTY** Preoperative condition is exceptionally complicated, exhibiting several factors listed in the MODERATE DIFFICULTY category or at least one in the HIGH DIFFICULTY category. Achieving a predictable treatment outcome will be challenging for even the most experienced practitioner with an extensive history of favorable outcomes.

Review your assessment of each case to determine the level of difficulty. If the level of difficulty exceeds your experience and comfort, you might consider referral to an endodontist.

The contribution of the Canadian Academy of Endodontics and others to the development of this form is gratefully acknowledged.

The AAE Endodontic Case Difficulty Assessment Form is designed to aid the practitioner in determining appropriate case disposition. The American Association of Endodontists neither expressly nor implicitly warrants any positive results associated with the use of this form. This form may be reproduced but may not be amended or altered in any way.

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## AAE Endodontic Case Difficulty Assessment Form

CRITERIA AND SUBCRITERIA	MINIMAL DIFFICULTY	MODERATE DIFFICULTY	HIGH DIFFICULTY
<b>A. PATIENT CONSIDERATIONS</b>			
<b>MEDICAL HISTORY</b>	<input type="checkbox"/> No medical problem (ASA Class 1*)	<input type="checkbox"/> One or more medical problems (ASA Class 2*)	<input type="checkbox"/> Complex medical history/serious illness/disability (ASA Classes 3-5*)
<b>ANESTHESIA</b>	<input type="checkbox"/> No history of anesthesia problems	<input type="checkbox"/> Vasoconstrictor intolerance	<input type="checkbox"/> Difficulty achieving anesthesia
<b>PATIENT DISPOSITION</b>	<input type="checkbox"/> Cooperative and compliant	<input type="checkbox"/> Anxious but cooperative	<input type="checkbox"/> Uncooperative
<b>ABILITY TO OPEN MOUTH</b>	<input type="checkbox"/> No limitation	<input type="checkbox"/> Slight limitation in opening	<input type="checkbox"/> Significant limitation in opening
<b>GAG REFLEX</b>	<input type="checkbox"/> None	<input type="checkbox"/> Gags occasionally with radiographs/treatment	<input type="checkbox"/> Extreme gag reflex which has compromised past dental care
<b>EMERGENCY CONDITION</b>	<input type="checkbox"/> Minimum pain or swelling	<input type="checkbox"/> Moderate pain or swelling	<input type="checkbox"/> Severe pain or swelling
<b>B. DIAGNOSTIC AND TREATMENT CONSIDERATIONS</b>			
<b>DIAGNOSIS</b>	<input type="checkbox"/> Signs and symptoms consistent with recognized pulpal and periapical conditions	<input type="checkbox"/> Extensive differential diagnosis of usual signs and symptoms required	<input type="checkbox"/> Confusing and complex signs and symptoms: difficult diagnosis <input type="checkbox"/> History of chronic oral/facial pain
<b>RADIOGRAPHIC DIFFICULTIES</b>	<input type="checkbox"/> Minimal difficulty obtaining/interpreting radiographs	<input type="checkbox"/> Moderate difficulty obtaining/interpreting radiographs (e.g., high floor of mouth, narrow or low palatal vault, presence of tori)	<input type="checkbox"/> Extreme difficulty obtaining/interpreting radiographs (e.g., superimposed anatomical structures)
<b>POSITION IN THE ARCH</b>	<input type="checkbox"/> Anterior/premolar <input type="checkbox"/> Slight inclination (<10°) <input type="checkbox"/> Slight rotation (<10°)	<input type="checkbox"/> 1st molar <input type="checkbox"/> Moderate inclination (10-30°) <input type="checkbox"/> Moderate rotation (10-30°)	<input type="checkbox"/> 2nd or 3rd molar <input type="checkbox"/> Extreme inclination (>30°) <input type="checkbox"/> Extreme rotation (>30°)
<b>TOOTH ISOLATION</b>	<input type="checkbox"/> Routine rubber dam placement	<input type="checkbox"/> Simple pretreatment modification required for rubber dam isolation	<input type="checkbox"/> Extensive pretreatment modification required for rubber dam isolation
<b>CROWN MORPHOLOGY</b>	<input type="checkbox"/> Normal original crown morphology	<input type="checkbox"/> Full coverage restoration <input type="checkbox"/> Porcelain restoration <input type="checkbox"/> Bridge abutment <input type="checkbox"/> Moderate deviation from normal tooth/root form (e.g., taurodontism, microdonts) <input type="checkbox"/> Teeth with extensive coronal destruction	<input type="checkbox"/> Restoration does not reflect original anatomy/alignment <input type="checkbox"/> Significant deviation from normal tooth/root form (e.g., fusion, dens in dente)
<b>CANAL AND ROOT MORPHOLOGY</b>	<input type="checkbox"/> Slight or no curvature (<10°) <input type="checkbox"/> Closed apex (<1 mm in diameter)	<input type="checkbox"/> Moderate curvature (10-30°) <input type="checkbox"/> Crown axis differs moderately from root axis. Apical opening 1-1.5 mm in diameter	<input type="checkbox"/> Extreme curvature (>30°) or S-shaped curve <input type="checkbox"/> Mandibular premolar or anterior with 2 roots <input type="checkbox"/> Maxillary premolar with 3 roots <input type="checkbox"/> Canal divides in the middle or apical third <input type="checkbox"/> Very long tooth (>25 mm) <input type="checkbox"/> Open apex (>1.5 mm in diameter)
<b>RADIOGRAPHIC APPEARANCE OF CANAL(S)</b>	<input type="checkbox"/> Canal(s) visible and not reduced in size	<input type="checkbox"/> Canal(s) and chamber visible but reduced in size <input type="checkbox"/> Pulp stones	<input type="checkbox"/> Indistinct canal path <input type="checkbox"/> Canal(s) not visible
<b>RESORPTION</b>	<input type="checkbox"/> No resorption evident	<input type="checkbox"/> Minimal apical resorption	<input type="checkbox"/> Extensive apical resorption <input type="checkbox"/> Internal resorption <input type="checkbox"/> External resorption
<b>C. ADDITIONAL CONSIDERATIONS</b>			
<b>TRAUMA HISTORY</b>	<input type="checkbox"/> Uncomplicated crown fracture of mature or immature teeth	<input type="checkbox"/> Complicated crown fracture of mature teeth <input type="checkbox"/> Subluxation	<input type="checkbox"/> Complicated crown fracture of immature teeth <input type="checkbox"/> Horizontal root fracture <input type="checkbox"/> Alveolar fracture <input type="checkbox"/> Intrusive, extrusive or lateral luxation <input type="checkbox"/> Avulsion
<b>ENDODONTIC TREATMENT HISTORY</b>	<input type="checkbox"/> No previous treatment	<input type="checkbox"/> Previous access without complications	<input type="checkbox"/> Previous access with complications (e.g., perforation, non-negotiated canal, ledge, separated instrument) <input type="checkbox"/> Previous surgical or nonsurgical endodontic treatment completed
<b>PERIODONTAL-ENDODONTIC CONDITION</b>	<input type="checkbox"/> None or mild periodontal disease	<input type="checkbox"/> Concurrent moderate periodontal disease	<input type="checkbox"/> Concurrent severe periodontal disease <input type="checkbox"/> Cracked teeth with periodontal complications <input type="checkbox"/> Combined endodontic/periodontic lesion <input type="checkbox"/> Root amputation prior to endodontic treatment

\*American Society of Anesthesiologists (ASA) Classification System

Class 1: No systemic illness. Patient healthy.

Class 2: Patient with mild degree of systemic illness, but without functional restrictions, e.g., well-controlled hypertension.

Class 3: Patient with severe degree of systemic illness which limits activities, but does not immobilize the patient.

Class 4: Patient with severe systemic illness that immobilizes and is sometimes life threatening.

Class 5: Patient will not survive more than 24 hours whether or not surgical intervention takes place.

[www.asahq.org/clinical/physicalstatus.htm](http://www.asahq.org/clinical/physicalstatus.htm)





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10<sup>th</sup> March 2016

Dear Fadi

I am pleased to say we are able to approve the request for ethical approval to undertake your research project. This is on condition that you abide by the requirements of the Human Tissue Act, and any other primary legislation that may govern the project.

Ref:	201612129
PI/Supervisor:	Fadi Jarad
Title:	The Use of CBCT as an Aid to Endodontic Access of Calcified Canals
First Reviewer:	David Taylor
Second Reviewer:	Helen Orton
Date of Approval:	9 <sup>th</sup> March 2016

The application was APPROVED subject to the following conditions:

Conditions

- 1 All serious adverse events must be reported to the Sub-Committee within 24 hours of their occurrence, via the Research Governance Officer ([ethics@liv.ac.uk](mailto:ethics@liv.ac.uk)).
- 2 This approval applies for the duration of the research. If it is proposed to extend the duration of the study as specified in the application form, IPHS REC should be notified as follows. If it is proposed to make an amendment to the research, you should notify IPHS REC by following the Notice of Amendment procedure outlined at <http://www.liv.ac.uk/researchethics/amendment%20procedure%209-08.doc>
- 3 If the named PI / Supervisor leaves the employment of the University during the course of this approval, the approval will lapse. Therefore please contact the Institute's Research Ethics Office at [iphsrec@liverpool.ac.uk](mailto:iphsrec@liverpool.ac.uk) in order to notify them of a change in PI/Supervisor.

Best wishes and good luck with the study.

Ann Furlong

*Ann Furlong*

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## References

- AAE (2005) Endodontic Case Difficult Assessment and Referral. *ENDODONTICS: Colleagues for Excellence*. Retrieved 18, January 2018 <http://www.aae.org/specialty/wp-content/uploads/sites/2/2017/07/ss05ecfe.pdf>
- ABELLA, F., AND KANAGASINGAM, S. (2016) in Patel, S., Harvey, S. C., Shemesh, H., & Durack, C. (Eds.). (2016). *Cone Beam Computed Tomography in Endodontics*.(pp. 67-78) Quintessence Publishing.
- ABOU-RASS, M. (1982). The stressed pulp condition: an endodontic-restorative diagnostic concept. *Journal of Prosthetic Dentistry*, 48(3), 264-267.
- AHMED, H.M.A., VERSIANI, M.A., DE-DEUS, G. AND DUMMER, P.M.H., 2017. A new system for classifying root and root canal morphology. *International endodontic journal*, 50(8), pp.761-770.
- ALGHAZALI, N., BURNSIDE, G., MOALLEM, M., SMITH, P., PRESTON, A., & JARAD, F. D. (2012). Assessment of perceptibility and acceptability of color difference of denture teeth. *Journal of dentistry*, 40, e10-e17.
- AMIR, F. A., GUTMANN, J. L. & WITHERSPOON, D. E. 2001. Calcific metamorphosis: A challenge in endodontic diagnosis and treatment. *Quintessence International*, 32, 447-455.
- ANDREASEN, F. M., ZHJIE, Y., THOMSEN, B. L. & ANDERSEN, P. K. 1987. Occurrence of pulp canal obliteration after luxation injuries in the permanent dentition. *Dental Traumatology*, 3, 103-115.
- ANDREASEN, J.O., 1970. Luxation of permanent teeth due to trauma A clinical and radiographic follow-up study of 189 injured teeth. *European Journal of Oral Sciences*, 78(1-4), pp.273-286.
- ASSADIAN, H., DABBAGHI, A., GOORAN, M., EFTEKHAR, B., SHARIFI, S., SHAMS, N., NAJVANI, A.D. AND TABESH, H., 2016. Accuracy of CBCT, Digital Radiography and Cross-Sectioning for the Evaluation of Mandibular Incisor Root Canals. *Iranian endodontic journal*, 11(2), p.106.
- AZIM, A. (2015). Management of a calcified Canal with guided troughing. Web video retrieved 4 Decemeber, 2017 from (<https://endolit.com/video/view/38>).
- BANDLISH, R. B., MCDONALD, A. V. & SETCHELL, D. J. 2006. Assessment of the amount of remaining coronal dentine in root-treated teeth. *Journal of Dentistry*, 34, 699-708.
- BASTONE, E. B., FREER, T. J. & MCNAMARA, J. R. 2000. Epidemiology of dental trauma: A review of the literature. *Australian Dental Journal*, 45, 2-9.
- BAUSS, O., NETER, D. AND RAHMAN, A., 2008. Prevalence of pulp calcifications in patients with Marfan syndrome. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*, 106(6), pp.e56-e61.
- BUCHGREITZ, J., BUCHGREITZ, M., MORTENSEN, D. & BJØRNDAL, L. 2015. Guided access cavity preparation using cone-beam computed tomography and optical surface scans - an ex vivo study. *International Endodontic Journal* 49(8), 790-795.
- BÜRKLEIN, S., HECK, R. AND SCHÄFER, E., 2017. Evaluation of the Root Canal Anatomy of Maxillary and Mandibular Premolars in a Selected German Population Using Cone-beam Computed Tomographic Data. *Journal of Endodontics*, 43(9), pp.1448-1452.

## References

- BYSTRÖM, A., & SUNDQVIST, G. (1981). Bacteriologic evaluation of the efficacy of mechanical root canal instrumentation in endodontic therapy. *European Journal of Oral Sciences*, 89(4), 321-328.
- BYSTRÖM, A., & SUNDQVIST, G. (1983). Bacteriologic evaluation of the effect of 0.5 percent sodium hypochlorite in endodontic therapy. *Oral Surgery, Oral Medicine, Oral Pathology*, 55(3), 307-312.
- BYUN, C., KIM, C., CHO, S., BAEK, S. H., KIM, G., KIM, S. G. & KIM, S. Y. 2015. Endodontic treatment of an anomalous anterior tooth with the aid of a 3-dimensional printed physical tooth model. *Journal of Endodontics*, 41, 961-965.
- CANTATORE, G., BERUTTI, E. & CASTELLUCCI, A. 2006. Missed anatomy: frequency and clinical impact. *Endodontic Topics*, 15, 3-31.
- CARTER, C. AND VEALÉ, B., 2013. *Digital Radiography and PACS-E-Book*. Elsevier Health Sciences.
- CHEN, M. H., CHEN, K. L., CHEN, C. A., TAYEBATY, F., ROSENBERG, P. A., & LIN, L. M. (2012). Responses of immature permanent teeth with infected necrotic pulp tissue and apical periodontitis/abscess to revascularization procedures. *International endodontic journal*, 45(3), 294-305.
- CLARK, D AND KHADEMI, J. 2009. Modern endodontic access and dentin conservation, part 1. *Dentistry Today*. 28(10): pp 86-90.
- CLARK, D AND KHADEMI, J. 2009. Modern endodontic access and dentin conservation, part 2. *Dentistry Today*. 28(11): pp 86-90.
- CLARK, D. & KHADEMI, J. 2010. Modern Molar Endodontic Access and Directed Dentin Conservation. *Dental Clinics of North America*, 54, 249-273.
- CLARKSON, B. H., LONGHURST, P. & SHEIHAM, A. 1973. The prevalence of injured anterior teeth in English schoolchildren and adults. *J Int Assoc Dent Child*, 4, 21-4.
- CONNERT, T., ZEHNDER, M.S., AMATO, M., WEIGER, R., KÜHL, S. AND KRASSTL, G., 2017. Microguided Endodontics: a method to achieve minimally invasive access cavity preparation and root canal location in mandibular incisors using a novel computer-guided technique. *International Endodontic Journal*. 51(2), 247-255.
- CONNERT, T., ZEHNDER, M.S., WEIGER, R., KÜHL, S. AND KRASSTL, G., 2017. Microguided Endodontics: Accuracy of a Miniaturized Technique for Apically Extended Access Cavity Preparation in Anterior Teeth. *Journal of Endodontics*, 43(5), pp.787-790.
- DE CLEEN, M. 2002. Obliteration of pulp canal space after concussion and subluxation: Endodontic considerations. *Quintessence International*, 33, 661-669.
- DE TOUBES, K.M.S., DE OLIVEIRA, P.A.D., MACHADO, S.N., PELOSI, V., NUNES, E. AND SILVEIRA, F.F., 2017. Clinical Approach to Pulp Canal Obliteration: A Case Series. *Iranian Endodontic Journal*, 12(4), pp.527-533.
- DEUTSCH, A. S. & MUSIKANT, B. L. 2004. Morphological Measurements of Anatomic Landmarks in Human Maxillary and Mandibular Molar Pulp Chambers. *Journal of Endodontics*, 30, 388-390.
- DEUTSCH, A. S., MUSIKANT, B. L., GU, S. & ISIDRO, M. 2005. Morphological Measurements of Anatomic Landmarks in Pulp Chambers of Human Maxillary Furcated Bicuspids. *Journal of Endodontics*, 31, 570-573.

## References

- EL WAZANI, B., DODD, M. N. & MILOSEVIC, A. 2012. The signs and symptoms of tooth wear in a referred group of patients. *British Dental Journal*, 213.
- FAYAD, M.I., NAIR, M., LEVIN, M.D., BENAVIDES, E., RUBINSTEIN, R.A., BARGHAN, S., HIRSCHBERG, C.S. AND RUPRECHT, A., 2015. AAE and AAOMR joint position statement: use of cone beam computed tomography in endodontics 2015 update. *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology*, 120(4), pp.508-512.
- GANZ, S. D. 2015. Three-Dimensional Imaging and Guided Surgery for Dental Implants. *Dental Clinics of North America*, 59, 265-290.
- GATTEN, D. L., RIEDY, C. A., HONG, S. K., JOHNSON, J. D. & COHENCA, N. 2011. Quality of life of endodontically treated versus implant treated patients: A university-based qualitative research study. *Journal of Endodontics*, 37, 903-909.
- GENG, W., LIU, C., SU, Y., LI, J. & ZHOU, Y. 2015. Accuracy of different types of computer-aided design/ computer-aided manufacturing surgical guides for dental implant placement. *International Journal of Clinical and Experimental Medicine*, 8, 8442-8449.
- GOGA, R., CHANDLER, N. P. & OGinni, A. O. 2008. Pulp stones: A review. *International Endodontic Journal*, 41, 457-468.
- GOMES, C.B.F., TREISTER, N.S., MILLER, B., ARMAND, P. AND FRIEDLAND, B., 2016. Pulp Obliteration in a Patient with Sclerodermatous Chronic Graft-versus-Host Disease. *Journal of Endodontics*, 42(4), pp.678-680.
- GRAUNAITE, I., LODIENE, G. & MACIULSKIENE, V. 2011. Pathogenesis of apical periodontitis: a literature review. *Journal of oral & maxillofacial research*, 2,(4)
- GULABIVALA, K., AUNG, T. H., ALAVI, A., & NG, Y. L. (2001). Root and canal morphology of Burmese mandibular molars. *International endodontic journal*, 34(5), 359-370.
- GULABIVALA, K., OPASANON, A., NG, Y. L., & ALAVI, A. (2002). Root and canal morphology of Thai mandibular molars. *International Endodontic Journal*, 35(1), 56-62.
- GUO, J., VAHIDNIA, A., SEDGHIZADEH, P. AND ENCISO, R., 2014. Evaluation of root and canal morphology of maxillary permanent first molars in a North American population by cone-beam computed tomography. *Journal of Endodontics*, 40(5), pp.635-639.
- GUTMANN, J. L. (1992). The dentin-root complex: anatomic and biologic considerations in restoring endodontically treated teeth. *The Journal of Prosthetic Dentistry*, 67(4), 458-467.
- HAAK, R, WICHT, M, HELLMICH, M, NOWAK, G, & NOACK, M 2002, 'Influence of room lighting on grey-scale perception with a CRT-and a TFT monitor display', *Dentomaxillofacial Radiology*, 31, 3, p. 193,
- HARRIS, R., & GRIFFIN, C. J. 1971. The ultrastructure of small blood vessels of the normal human dental pulp. *Australian dental journal*, 16(4), 220-226.
- HARVEY, S.C. AND PATEL, S. 2016 Using CBCT: Dose, Risk and Artefacts. In in Patel, S., Harvey, S. C., Shemesh, H., & Durack, C. (Eds.). (2016). *Cone Beam Computed Tomography in Endodontics*.(pp. 43-53) Quintessence Publishing.
- HASSELGREN, G. AND STRÖMBERG, T., 1976. The use of iodine as a contrast medium in endodontic therapy. *Oral Surgery, Oral Medicine, Oral Pathology*, 41(6), pp.785-788.
- HASSELGREN, G., 1988. The prognosis for endodontic treatment of obliterated root canals. *Journal of Endodontics*, 14(11), pp.565-567.

## References

- HOLAN, G. 1998. Tube-like mineralization in the dental pulp of traumatized primary incisors. *Endodontics and Dental Traumatology*, 14, 279-284.
- HOLCOMB, J. B. & GREGORY, W. B., JR. 1967. Calcific metamorphosis of the pulp: its incidence and treatment. *Oral Surg Oral Med Oral Pathol*, 24, 825-30.
- JACOBSEN, I. AND SANGNES, G., 1978. Traumatized primary anterior teeth: prognosis related to calcific reactions in the pulp cavity. *Acta Odontologica Scandinavica*, 36(4), pp.199-204.
- JI, Y., WEN, S., LIU, S., ZHU, M., YAO, M., WANG, T. AND LIN, Z., 2017. Could cone-beam computed tomography demonstrate the lateral accessory canals?. *BMC Oral Health*, 17(1), p.142.
- KELEŞ, A., & KESKIN, C. (2018). A micro-computed tomographic study of band-shaped root canal isthmuses, having their floor in the apical third of mesial roots of mandibular first molars. *International endodontic journal*, 51(2), 240-246.
- KIEFNER, P., CONNERT, T., ELAYOUTI, A. AND WEIGER, R., 2017. Treatment of calcified root canals in elderly people: a clinical study about the accessibility, the time needed and the outcome with a three-year follow-up. *Gerodontology*, 34(2), pp.164-170.
- KRASNER, P. & RANKOW, H. J. 2004. Anatomy of the Pulp-Chamber Floor. *Journal of Endodontics*, 30, 5-16.
- KRASTL, G., ZEHNDER, M.S., CONNERT, T., WEIGER, R. AND KÜHL, S., 2016. Guided Endodontics: a novel treatment approach for teeth with pulp canal calcification and apical pathology. *Dental Traumatology*, 32(3), pp.240-246.
- KRISHAN, R., PAQUÉ, F., OSSAREH, A., KISHEN, A., DAO, T. & FRIEDMAN, S. 2014. Impacts of conservative endodontic cavity on root canal instrumentation efficacy and resistance to fracture assessed in incisors, premolars, and molars. *Journal of Endodontics*, 40, 1160-1166.
- KUTTLER, Y. 1959. Classification of dentine into primary, secondary, and tertiary. *Oral Surgery, Oral Medicine, Oral Pathology*, 12, 996-1001.
- KUYK, J. K. & WALTON, R. E. 1990. Comparison of the radiographic appearance of root canal size to its actual diameter. *Journal of Endodontics*, 16, 528-533.
- LEE, M. M., RASIMICK, B. J., TURNER, A. M., SHAH, R. P., MUSIKANT, B. L. & DEUTSCH, A. S. 2007. Morphological Measurements of Anatomic Landmarks in Pulp Chambers of Human Anterior Teeth. *Journal of Endodontics*, 33, 129-131.
- LIMA, T. F. R., SOUZA-FILHO, F. J. & SOARES, A. J. 2014. Cone-beam computed tomography as a diagnostic tool to locate calcified canals. *Dental Press Endodontics*, 4, 74-78.
- LUNDBERG, M. & CVEK, M. 1980. A light microscopy study of pulps from traumatized permanent incisors with reduced pulpal lumen. *Acta Odontologica Scandinavica*, 38, 89-94.
- MAH, P., MCDAVID, W.D. AND DOVE, S.B., 2011. Quality assurance phantom for digital dental imaging. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*, 112(5), pp.632-639.
- MALHOTRA, N. & MALA, K. 2013. Calcific metamorphosis. Literature review and clinical strategies. *Dental Update*, 40, 48-50, 53-4, 57-8 passim.
- MASCARENHAS, V. I., DE MOLON, R. S., TAVARES, L. J., MENDES, L. M. F., TONETTO, M. R. & BANDECA, M. C. 2014. The use of computer guided implant surgery in oral rehabilitation: A literature review. *World Journal of Dentistry*, 5, 60-63.

## References

- MATHERNE, R. P., ANGELOPOULOS, C., KULILD, J. C. & TIRA, D. 2008. Use of Cone-Beam Computed Tomography to Identify Root Canal Systems In Vitro. *Journal of Endodontics*, 34, 87-89.
- MCCABE, P. S. & DUMMER, P. M. H. 2012. Pulp canal obliteration: An endodontic diagnosis and treatment challenge. *International Endodontic Journal*, 45, 177-197.
- MCCABE, P. S. 2006. Avoiding perforations in endodontics. *Journal of the Irish Dental Association*, 52, 139-148.
- MICHETTI, J., MARET, D., MALLET, J.P. AND DIEMER, F., 2010. Validation of cone beam computed tomography as a tool to explore root canal anatomy. *Journal of Endodontics*, 36(7), pp.1187-1190.
- MIRMOHAMMADI, H., MAHDI, L., PARTOVI, P., KHADEMI, A., SHEMESH, H. and Hassan, B., 2015. Accuracy of cone-beam computed tomography in the detection of a second mesiobuccal root canal in endodontically treated teeth: an ex vivo study. *Journal of Endodontics*, 41(10), pp.1678-1681.
- MOLVEN, O. 1973. Nonpenetrable root canals as assessed by a standardized instrumentation procedure. *Oral Surgery, Oral Medicine, Oral Pathology*, 35, 232-237.
- MORITA INC. 2017. Accuitomo Overview Webpage Retrieved December, 20 2017 from <http://www.morita.com/america/en/products/diagnostic-and-imaging-equipment/cone-beam-ct-systems/3d-accuitomo-170/?tab=highlights>)
- MURRAY, P. E., STANLEY, H. R., MATTHEWS, J. B., SLOAN, A. J. & SMITH, A. J. 2002. Age-related odontometric changes of human teeth. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics*, 93, 474-482.
- NAIR, M.K. AND NAIR, U.P., 2007. Digital and advanced imaging in endodontics: a review. *Journal of Endodontics*, 33(1), pp.1-6.
- NAIR, P. N. 2006. On the causes of persistent apical periodontitis: a review. *International Endodontic Journal*, 39, 249-81.
- NAIR, P. N., SUNDQVIST, G. & SJOGREN, U. 2008. Experimental evidence supports the abscess theory of development of radicular cysts. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics*, 106, 294-303.
- NANCE, R., TYNDALL, D., LEVIN, L. & TROPE, M. 2000. Identification of root canals in molars by tuned-aperture computed tomography. *International Endodontic Journal*, 33, 392-396.
- NAOUM, H.J., LOVE, R.M., CHANDLER, N.P. AND HERBISON, P., 2003. Effect of X-ray beam angulation and intraradicular contrast medium on radiographic interpretation of lower first molar root canal anatomy. *International endodontic journal*, 36(1), pp.12-19.
- NEELAKANTAN, P., SUBBARAO, C. & SUBBARAO, C. V. 2010b. Comparative Evaluation of Modified Canal Staining and Clearing Technique, Cone-Beam Computed Tomography, Peripheral Quantitative Computed Tomography, Spiral Computed Tomography, and Plain and Contrast Medium-enhanced Digital Radiography in Studying Root Canal Morphology. *Journal of Endodontics*, 36, 1547-1551.
- NEELAKANTAN, P., SUBBARAO, C., AHUJA, R., SUBBARAO, C. V. & GUTMANN, J. L. 2010a. Cone-Beam Computed Tomography Study of Root and Canal Morphology of Maxillary First and Second Molars in an Indian Population. *Journal of Endodontics*, 36, 1622-1627.

## References

- NEVES, V. C. M., & SHARPE, P. T. (2018). Regulation of Reactionary Dentine Formation. *Journal of dental research*, 97(4), 416-422.
- NG, C. C. H., DUMBRIGUE, H. B., AL-BAYAT, M. I., GRIGGS, J. A. & WAKEFIELD, C. W. 2006. Influence of remaining coronal tooth structure location on the fracture resistance of restored endodontically treated anterior teeth. *The Journal of Prosthetic Dentistry*, 95, 290-296.
- NG, Y. L., MANN, V. & GULABIVALA, K. 2011. A prospective study of the factors affecting outcomes of non-surgical root canal treatment: Part 2: Tooth survival. *International Endodontic Journal*, 44, 610-625.
- NG, Y. L., MANN, V., RAHBARAN, S., LEWSEY, J. & GULABIVALA, K. 2007. Outcome of primary root canal treatment: systematic review of the literature—Part 1. Effects of study characteristics on probability of success. *International endodontic journal*, 40, 921-939.
- NGEOW, W. C. & THONG, Y. L. 1998. Gaining access through a calcified pulp chamber: A clinical challenge. *International Endodontic Journal*, 31, 367-371.
- OGINNI, A. O. & ADEKOYA-SOFOWORA, C. A. 2007. Pulpal sequelae after trauma to anterior teeth among adult Nigerian dental patients. *BMC Oral Health*, 7.
- OGINNI, A. O., ADEKOYA-SOFOWORA, C. A. & KOLAWOLE, K. A. 2009. Evaluation of radiographs, clinical signs and symptoms associated with pulp canal obliteration: An aid to treatment decision. *Dental Traumatology*, 25, 620-625.
- PARKER, J., MOL, A., RIVERA, E.M. AND TAWIL, P., 2017. CBCT uses in clinical endodontics: the effect of CBCT on the ability to locate MB2 canals in maxillary molars. *International endodontic journal*. 50(12), 1109-1115.
- PATEL, S., DAWOOD, A., FORD, T. P. & WHAITES, E. 2007. The potential applications of cone beam computed tomography in the management of endodontic problems. *International Endodontic Journal*, 40, 818-830.
- PATEL, S., DURACK, C., ABELLA, F., ROIG, M., SHEMESH, H., LAMBRECHTS, P. AND LEMBERG, K., 2014. European Society of Endodontology position statement: the use of CBCT in endodontics. *International endodontic journal*, 47(6), pp.502-504.
- PATEL, S., DURACK, C., ABELLA, F., SHEMESH, H., ROIG, M. & LEMBERG, K. 2015. Cone beam computed tomography in Endodontics - a review. *International Endodontic Journal*, 48, 3-15.
- PATEL, S., HARVEY, S. C., SHEMESH, H., & DURACK, C. (Eds.). (2016). *Cone Beam Computed Tomography in Endodontics*. Quintessence Publishing.
- PETERSEN, P. E., BOURGEOIS, D., OGAWA, H., ESTUPINAN-DAY, S. & NDIAYE, C. 2005. The global burden of oral diseases and risks to oral health. *Bulletin of the World Health Organization*, 83, 661-669.
- PHILIPPAS, G. G. 1961. Influence of occlusal wear and age on formation of dentin and size of pulp chamber. *Journal of Dental Research*, 40, 1186-98.
- PIATTELLI, A. & TRISI, P. 1993. Pulp obliteration: A histological study. *Journal of Endodontics*, 19, 252-254.
- PIATTELLI, A., 1992. Generalized "complete" calcific degeneration or pulp obliteration. *Dental Traumatology*, 8(6), pp.259-263.
- RAY, H. & TROPE, M. 1995. Periapical status of endodontically treated teeth in relation to the technical quality of the root filling and the coronal restoration. *International Endodontic Journal*, 28, 12-18.

## References

- RAY, H. A., & TROPE, M. (1995). Periapical status of endodontically treated teeth in relation to the technical quality of the root filling and the coronal restoration. *International endodontic journal*, 28(1), 12-18.
- REEH, E. S., MESSER, H. H. & DOUGLAS, W. H. 1989. Reduction in tooth stiffness as a result of endodontic and restorative procedures. *Journal of Endodontics*, 15, 512-516.
- REES, J. S., THOMAS, M. & NAIK, P. 2011. A prospective study of the prevalence of periapical pathology in severely worn teeth. *Dental update*, 38, 24-26, 28-29.
- RITTER, L., PALMER, J., BINDL, A., IRSEN, S., CIZEK, J., KARAPETIAN, V. E. & ZOLLER, J. E. 2014. Accuracy of chairside-milled CAD/CAM drill guides for dental implants. *International journal of computerized dentistry*, 17(2), 115-124.
- ROBERTSON, A., ANDREASEN, F. M., BERGENHOLTZ, G., ANDREASEN, J. O. & NORÉN, J. G. 1996. Incidence of pulp necrosis subsequent to pulp canal obliteration from trauma of permanent incisors. *Journal of Endodontics*, 22, 557-560.
- ROBERTSON, A., LUNDGREN, T., ANDREASEN, J.O., DIETZ, W., HOYER, I. AND NORÉN, J.G., 1997. Pulp calcifications in traumatized primary incisors A morphological and inductive analysis study. *European journal of oral sciences*, 105(3), pp.196-206.
- ROSEN, E., TASCHIERI, S., DEL FABBRO, M., BEITLITUM, I. AND TSESIS, I., 2015. The diagnostic efficacy of cone-beam computed tomography in endodontics: a systematic review and analysis by a hierarchical model of efficacy. *Journal of Endodontics*, 41(7), pp.1008-1014.
- SALEHRABI, R. & ROTSTEIN, I. 2004. Endodontic treatment outcomes in a large patient population in the USA: an epidemiological study. *Journal of Endodontics*, 30, 846-50.
- SAUNDERS, W. P. 2014. Treatment planning the endodontic-implant interface. *British Dental Journal*, 216, 325-330.
- SCHULZE, R., HEIL, U., GROB, D., BRUELLMANN, D. D., DRANISCHNIKOW, E., SCHWANECKE, U., & SCHOEMER, E. (2011). Artefacts in CBCT: a review. *Dentomaxillofacial Radiology*, 40(5), 265-273.
- SELDEN, H. S. 1989. The role of a dental operating microscope in improved nonsurgical treatment of "calcified" canals. *Oral Surgery, Oral Medicine, Oral Pathology*, 68, 93-98.
- SILVA, E.J.N.L., NEJAIM, Y., SILVA, A.I., HAITER-NETO, F., ZAIA, A.A. AND COHENCA, N., 2014. Evaluation of root canal configuration of maxillary molars in a Brazilian population using cone-beam computed tomographic imaging: an in vivo study. *Journal of Endodontics*, 40(2), pp.173-176.
- SOARES DE TOUBES, K. M. P., CÔRTEZ, M. I. D. S., VALADARES, M. A. D. A., FONSECA, L. C., NUNES, E. & SILVEIRA, F. F. 2012. Comparative Analysis of Accessory Mesial Canal Identification in Mandibular First Molars by Using Four Different Diagnostic Methods. *Journal of Endodontics*, 38, 436-441.
- STRBAC, G.D., SCHNAPPAUF, A., GIANNIS, K., MORITZ, A. AND ULM, C., 2017. Guided Modern Endodontic Surgery: A Novel Approach for Guided Osteotomy and Root Resection. *Journal of Endodontics*, 43(3), pp.496-501.
- TAVARES, W., LOPES, R., MENEZES, G., HENRIQUES, L., & RIBEIRO, A. (2012). Nonsurgical treatment of pulp canal obliteration using contemporary endodontic techniques: Case series. *Clinical Case*, 2(1), 52-58.



## References

- TIAN, Y.Y., GUO, B., ZHANG, R., YU, X., WANG, H., HU, T. AND DUMMER, P.M.H., 2012. Root and canal morphology of maxillary first premolars in a Chinese subpopulation evaluated using cone-beam computed tomography. *International Endodontic Journal*, 45(11), pp.996-1003.
- VAN DER MEER, W.J., VISSINK, A., NG, Y.L. AND GULABIVALA, K., 2016. 3D Computer aided treatment planning in endodontics. *Journal of Dentistry*, 45, pp.67-72.
- VENSKUTONIS, T., PLOTINO, G., JUODZBALYS, G. AND MICKEVIČIENĖ, L., 2014. The importance of cone-beam computed tomography in the management of endodontic problems: a review of the literature. *Journal of Endodontics*, 40(12), pp.1895-1901.
- VIZZOTTO, M. B., DA SILVEIRA, P. F., LIEDKE, G. S., ARUS, N. A., MONTAGNER, F., SILVEIRA, H. L. D. & SILVEIRA, H. E. D. 2015. Diagnostic reproducibility of the second mesiobuccal canal by CBCT: influence of potential factors. *Oral Radiology*, 31, 160-164.
- VIZZOTTO, M. B., SILVEIRA, P. F., ARÚS, N. A., MONTAGNER, F., GOMES, B. P. F. A. & DA SILVEIRA, H. E. D. 2013. CBCT for the assessment of second mesiobuccal (MB2) canals in maxillary molar teeth: Effect of voxel size and presence of root filling. *International Endodontic Journal*, 46, 870-876.
- WEINE, F. S., Healey, H. J., Gerstein, H., & Evanson, L. (1969). Canal configuration in the mesiobuccal root of the maxillary first molar and its endodontic significance. *Oral Surgery, Oral Medicine, Oral Pathology*, 28(3), 419-425.
- WHITE, S. C., & PHAROAH, M. J. (2014). *Oral radiology-E-Book: Principles and interpretation*. Elsevier Health Sciences.
- WORTHINGTON, P., RUBENSTEIN, J. & HATCHER, D. C. 2010. The role of cone-beam computed tomography in the planning and placement of implants. *The Journal of the American Dental Association*, 141 Suppl 3, 19s-24s.
- YAN, W.A.N.G., TAO, P. AND YING, Z., 2012. The Morphological Study of Maxillary First Molar Mesiobuccal Canal with Cone-beam Computed Tomography. *Journal of Oral Science Research*, 9, p.038.
- YANG, Y.M., GUO, B., GUO, L.Y., YANG, Y., HONG, X., PAN, H.Y., ZOU, W.L. AND HU, T., 2016. CBCT-Aided Microscopic and Ultrasonic Treatment for Upper or Middle Thirds Calcified Root Canals. *BioMed research international*, 2016.
- YU, X., GUO, B., LI, K.Z., ZHANG, R., TIAN, Y.Y. AND WANG, H., 2012. Cone-beam computed tomography study of root and canal morphology of mandibular premolars in a western Chinese population. *BMC medical imaging*, 12, pp.18-18.
- ZEHNDER, M.S., CONNERT, T., WEIGER, R., KRSTL, G. AND KÜHL, S., 2016. Guided endodontics: accuracy of a novel method for guided access cavity preparation and root canal location. *International Endodontic Journal*, 49(10), pp.966-972.
- ZUBIZARRETA MACHO, Á., FERREIROA, A., RICO-ROMANO, C., ALONSO-EZPELETA, L. Ó. & MENA-ÁLVAREZ, J. 2015. Diagnosis and endodontic treatment of type II dens invaginatus by using cone-beam computed tomography and splint guides for cavity access: A case report. *The Journal of the American Dental Association*, 146, 266-270.