DETERMINING THE ACCURACY OF A CONE-BEAM COMPUTED TOMOGRAPHY MACHINE FOR MEASURING THE DIMENSIONS OF ENAMEL AND DENTINE

Tjiane Idah Mmutlana

Student Number: 699045

A research report submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the Degree of Master of Dentistry in Prosthodontics.

Johannesburg, 2017

DECLARATION

I, Tjiane Idah Mmutlana, declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Dentistry in Prosthodontics. It has not been submitted before for any degree or examination at this or any other institution.

____

Tjiane Idah Mmutlana

24 October 2017

DEDICATION

I dedicate this to my loving and supportive parents, Marcus and Virginia Mmutlana and my children Lesedi and Khumo.

ACKNOWLEDGEMENTS

I would like to thank:

Professor Peter Owen for all his inspiration, motivation, and patience in the initiation and creation of this research project. He helped me understand the true importance and joy in research in the field of dental science.

Dr Meriting Thokoane for her invaluable guidance, encouragement and mentorship throughout the process of this research write up.

Mr Dion Van Zyl for all his assistance in statistical analysis.

The staff in the Department of Radiology at the Wits Oral Health Science Centre, in particular Mrs Ayesha Asmal who was the second evaluator in the study.

The Department of Oral Rehabilitation, University of Witwatersrand, Johannesburg, where I am registered as a postgraduate student

ABSTRACT

Introduction

Pulpal damage in response to tooth preparation is an undesirable result and a major concern in the practice of fixed prosthodontics. The purpose of this study was to determine the accuracy and reliability of using Cone Beam Computed Tomography (CBCT) measuring software to make linear measurements of enamel and dentine. In this manner the preoperative measurements of dentine could be determined to prevent over-preparation.

Materials and Methods

Sixteen extracted permanent premolars and molars which had been stored in sterile water were sectioned in a bucco-lingual direction, numbered for identification, embedded in a typodont model and a CBCT image taken. There were 21 tooth sections and 14 aspects of each section were measured to provide a total sample of 294 measurements. Measurements of the width of enamel and dentine were first made with digital callipers independently by two evaluators, who then subsequently made the same measurements using the CBCT software. Intra-class Correlations were used to determine the inter-rater correlations. The Bland-Altman test was used to compare the two measurement techniques to determine their limits of agreement and whether these were clinically relevant.

Results

Both methods were found to be reliable (r=0.999). CBCT measurements were slightly higher than calliper measurements in about 60 percent of all measurements. The Bland-Altman analysis determined the limits of agreement to range between -0.04mm and -0.140mm, with 95% of the values residing within this range.

Conclusion

The margin of error between the two types of measurements translates to between 4 and 140μm of tooth dentine or enamel thickness. As this is less than the 500 μm minimum width of residual dentine at which histological changes in the dentino-pulpal complex can be observed after preparation, the two methods can be used interchangeably to measure tooth dimensions of enamel and dentine.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 A BRIEF ACCOUNT OF THE ROLE OF RADIOGRAPHY IN DENTISTRY

For many years, dental radiography was used to aid diagnosis and treatment planning and largely comprised panoramic, intraoral and cephalometric views, all of which provide two-dimensional imaging of oral hard tissues (Wenzel, 1998; Boeddinghaus and Whyte, 2008). As a result, superimposition of adjacent structures may occur, resulting in distortion and/ or magnification of the image obtained (Scarfe and Farman, 2008). Because of this overlapping of structures, the identification of specific landmarks may become unclear, rendering image interpretation difficult (Liang et al, 2010).

1.2 COMPUTED TOMOGRAPHY

The development of computed tomography (CT) promised to provide an opportunity for three dimensional (3D) imaging and assessment of craniofacial structures (Liang et al, 2010).

Images in traditional CT are produced by means of a fan shaped X-ray beam which projects attenuation patterns onto a series of detectors arranged in an arc shaped pattern. The sum of all attenuation patterns produces an image of a slice of tissue per rotation. Several rotations in different planes produce several image slices which can be assimilated or “stacked up” to reconstruct a three dimensional image (Scarfe and Farman, 2008).

Cone beam CT (CBCT) on the other hand uses a cone-shaped beam which penetrates sequentially through block of tissue of interest in a single rotation. (Scarfe and Farman, 2008; Kiljunen et al, 2015).

The principle of image formation is similar to that of conventional CT i.e. the sum of attenuation patterns projected onto a series of detectors. However a block of tissue is represented rather than a slice resulting in poorer resolution of detail as compared to conventional CT. A series of two-dimensional images are produced which can be viewed in a variety of planes; also through advanced computer software 3D volumetric data sets can be reconstructed from which 3D images can be formed (Sakabe et al, 2007).

Historically, the application of three-dimensional imaging in the form of conventional CT has been limited due to cost, availability and considerations of heavy radiation dosage. The introduction of cone beam technology has therefore provided the opportunity to achieve relatively high quality three-dimensional representation of the maxillofacial region with minimal distortion, less cost and less radiation exposure.

The introduction of CBCT to dentistry was pioneered by Italian inventors Attilio Tacconi and Piero Mozzo in 1995 with the first maxillofacial imaging device known as the NewTom DVT 9000 (Mozzo et al, 1998; Scarfe et al, 2006). The device was commercially introduced in Europe in 1999. At the same time, Arai and colleagues had also introduced their device in Japan.

Advancement in the technology of the hardware (i.e. X-ray tubes, detector systems and personal computers) and software programmes has made CBCT systems more affordable and commercially available over the years (Scarfe and Farman, 2007).

1.3 ADVANTAGES OF CONE BEAM COMPUTED TOMOGRAPHY IN MAXILLOFACIAL IMAGING AND DENTISTRY

CBCT provides clear images of high contrast and is therefore a useful tool in the evaluation of maxillofacial structures, particularly when evaluating bony structures (Honda et al, 2004). The technology provides several superior features which allow for the following characteristics:

1.3.1 Radiation dose reduction

CBCT units acquire the required data using a single complete or partial rotation which exposes the entire field of view on a single detector and significantly reduces the radiation dose when compared with conventional CT (Kiljunen et al, 2015). Dose reductions ranging between 76.2 percent and 98.5 percent have been reported in the literature when comparing conventional CT and CBCT for maxillofacial imaging (Dula et al, 1996; Scaf et al, 1997, Schulze et al, 2004)

1.3.2 X-ray beam limitation

CBCT uses a collimated source of x-ray. A collimator is a device incorporated into the X-ray machine head consisting of a metallic barrier which has an aperture in the middle. It reduces or narrows the size of the X-ray beam that penetrates the tissue, either by directing the beam in one specific direction, which in this case would be through the aperture only, or by reducing the cross section of the beam, which would be determined by the cross-sectional size of the aperture. This leads to reduction of the size of the irradiated area and limits the radiation to the chosen field of interest only (Scarfe et al, 2006; Scarfe and Farman, 2008). This minimises the radiation dosage to the patient. While CBCT units are capable of scanning the entire craniofacial region, they can also be adjusted to scan small regions for specific diagnostic purposes (Scarfe et al, 2006).

1.3.3 Image accuracy

The smallest element of volumetric data (a voxel), determines the resolution of the image (Qu et al, 2011). The smaller the voxel size, the sharper the image. It also represents the degree of x-ray absorption, meaning that for a sharper image the radiation dosage and absorption would have to be higher (Scarfe et al, 2006; Ganguly et al, 2016). While the depth of voxels in conventional CT can be as small as a millimetre, the CBCT units provide voxel resolutions that are isotropic (of equal height, depth and width) thus providing submillimetre resolution. CBCT can therefore provide sharper images of highly contrasted structures and is extremely useful for evaluating bone (Scarfe et al, 2006).

1.3.4 Reduced scanning time and artefacts

Image artefacts may occur due to patient movement during acquisition. In CBCT scanning, a single rotation can be achieved within 10 to 70 seconds. In this relatively short duration the chances of the subject /patient moving are reduced thus reducing the likely occurrence of artefacts (Scarfe et al, 2006; Scarfe and Farman, 2008). In addition, manufacturers have incorporated artefact suppression algorithms which result in low levels of artefacts caused by metal objects within the image such as restorations and reconstruction plates (Cohnen et al, 2002).

1.3.5 Ease of accessibility and display modes unique to maxillofacial imaging

More recent types of detectors are flat panel detectors which have been made to be less bulky, uncomplicated and offer higher spatial resolution (Nemtoi et al, 2013; Kiljunen et al

2015). This has allowed for the manufacture of compact units which can be established in small clinical practices, thus increasing ease of access at a relatively reduced cost (Scarfe and Farman, 2008). From an economic perspective, the CBCT X-ray tube has now been fitted with technical specifications for acquiring panoramic views thus avoiding multiple unit costs (Kiljunen et al, 2015).

1.3.6 Ease of use

The incorporated software allows for basic enhancements such as zooming or magnification and visual adjustments of the grey scales as well as the level of contrast within the window of view (Scarfe et al, 2006). It also enables the addition of annotations, and cursor-driven linear measurements of anatomical structures such as bone width and height, as well as virtual surgery and implant placement. Variation in contrast can be adjusted on acquisition and during viewing, a significant aspect when assessing osseous structures in the maxillofacial region (Scarfe and Farman, 2008; Liang et al. 2010).

In summary CBCT has created a true paradigm shift in maxillofacial radiology even though conventional CT had existed before.

1.4 APPLICATIONS OF CBCT IN DENTISTRY

Reported uses of CBCT in dentistry range from orthodontic assessments of tooth anomalies (Kim et al, 2003), studies evaluating airway abnormalities (Hatcher, 2012), endodontic studies (Asgary et al, 2016), age estimation studies (Ge et al, 2015), tooth width measurement studies(Baumgaertel et al, 2009), oral and maxillofacial assessment of various conditions such as impacted teeth, pathological lesions as well as for virtual surgery planning, implant planning, bone density evaluation and a whole host of other applications (Sakabe et al, 2007).

1.4.1 The application of CBCT in prosthodontics

Reported literature regarding the application of CBCT in prosthodontics is largely related to its application in implant dentistry and with regard to planning of implant placement and surgical guide fabrication (Worthington et al, 2010). In conjunction with data from intraoral digital scanners, it allows for three-dimensional printing and precision milling of immediate provisional fixed prostheses (Joda and Bragger, 2015). Other areas where CBCT has been reported in prosthodontics is in TMJ imaging (Larheim et al, 2015) and craniofacial reconstructions in maxillofacial prosthodontics (Sarment, 2014). There have been suggestions in the literature to use CBCT for monitoring bone resorption rates in denture wearers over several years; however this was a single study that cannot be substantiated with follow-up or similar studies (John et al, 2016).

1.5 CBCT *VS.* LINEAR MEASUREMENTS

Recently there has been a gradual increase in research involving the comparison of actual linear measurements to those obtained through digital CBCT tools in order to establish the accuracy of the latter and to validate its clinical application. In several studies ranging from orthodontic tooth width measurements to tooth impaction scenarios, there seems to be general consensus that 3D apparatus are able to give accurate measurements in the plane of interest and it confirms their clinical reliability meaning that the differences between the physical and CBCT measurements are statistically insignificant (Baumgaertel et al, 2009; Radeke et al, 2014; Grunheid et al, 2014). The reproducibility of the measurements was evaluated by comparing measurements of the same objects by different observers, while accuracy was compared between a CBCT measurement and a manual device e.g. a digital calliper or a laboratory measuring apparatus. These studies reported no significant differences in the CBCT measurements obtained by different observers. There were also observed differences between the clinical measurements and CBCT measurements but these were considered to be clinically insignificant.

Several studies have explored the accuracy of inter-landmark linear measurements on anatomical structures within the skull (Veyre-Goulet *et al*, 2008; Berco *et al*, 2009) and concluded that there were no clinically significant differences between the measurements obtained by cone beam images and the actual anatomic measurements obtained directly on the skull. Despite the complexity of the maxillary structures and the noise of scatter which slightly compromised the quality of the images in the former study, the results obtained showed no intra-operator or inter-operator differences and measurement errors detected were of no clinical significance.

Moshfeghi *et al*. (2012) concluded that CBCT is "highly accurate and reproducible in linear tooth width measurements in the axial and coronal planes and in different areas of the maxillofacial region". Benninger *et al* (2012) reported the use of CBCT to assess actual tooth height and width from cone beam images of teeth extracted from cadavers. They found no statistically significant differences in the average values of the CBCT-imaged values using the measuring software programme, and the actual post-extraction tooth dimension values using digital callipers.

1.6 CROWN PREPARATIONS AND TOOTH DIMENSIONS

1.6.1 Pulpal damage during crown preparation

Extra-coronal tooth-supported restorations have been used for many years to restore form and function of teeth that have been subjected to trauma or caries and to replace missing teeth. The success of the restoration is dependent on the interaction of three primary factors namely

1) the design of the tooth preparation, 2) fit of the restoration and the 3) choice of cement. Tooth preparation and the follow up clinical steps that are involved in fixed prosthodontics, such as impression taking (Langeland and Langeland, 1965), provisionalisation (Seelbach et al, 2010) and cementation (Pontes et al, 2014) of the prosthesis, have all been shown in the literature to pose a threat to the integrity of the pulp, and are in one way or another a source of insult thereto (Jackson et al, 1992).

Measurements of the amount of tooth structure that needs to be removed have historically been based on principles such as the mechanical principles of resistance and retention, occlusal requirements, as well as the type of material from which the crown is fabricated. All these serve to prevent the crown from being dislodged (Shillingburg et al, 2012)

Despite positive outcomes as depicted by longevity studies of extra-coronal restorations, undesirable results that may be associated with over-preparation of teeth such as secondary caries and pulpal degradation have been reported (Walton et al, 1986; Valderhaug et al, 1997; De Backer et al, 2006). These may lead to restoration failure, the need for endodontic treatment and/or subsequent loss of abutment teeth. Other studies have reported the need for endodontic treatment following the placement of a fixed restoration (Jackson et al, 1992; Walton, 1999). Long-span fixed prostheses, due to their complex structure, lead to over-contouring and over-tapering of abutment teeth which increase the probability of pulpal damage and necrosis (Valderhaug et al, 1997).

The risk factors which affect the pulp during tooth preparation include the amount of heat generated by rotary instruments, the speed of the rotary instruments as well as drilling techniques. These factors have been associated with the following :inadequate use of coolant, application of pressure on the tooth, the use of chemicals to treat the tooth, drying of the dentine, incorporation of microorganisms (Zach & Cohen, 1965; Seltzer& Bender, 1958), and the width of the remaining dentine after preparation (Stanley, 1994).

Thus far studies on pulpal changes have highlighted the impact of the combination of heating the pulp and cutting the dentinal tubules (Zach and Cohen, 1965). In most of these studies excessive heating has been highlighted as the most serious source of insult to the pulp. It has also been reported that there are risk factors after the preparation, such as air drying and pressure during impression taking and cementation, (Al-Fawaz et al, 1993).

1.6.2 The dimensions of residual dentine

The amount of residual dentine will influence the extent to which pulpal tissue will respond to mechanical, chemical and thermal insult after tooth preparation. Studies have suggested, from evidence of the histological changes observed within the odontoblasts when chemical agents were used during restorative procedures, that 2mm or more of remaining dentine thickness was critical for preventing irreversible damage to the pulp (Stanley, 1994; Murray et al, 2003). There has been some controversy in the literature, though, where some studies have reported that even 1.0 mm is sufficient to protect the pulp from the cytotoxic effects of cements such as zinc phosphate and glass ionomer (Pameijer et al, 1991), while others have reported that residual dentine thickness as minimal as 0.5 mm has little effect on odontoblasts per unit area (Murray et al, 2000). Even though there is no consensus in the literature regarding the dimension of the remaining dentine thickness, 2.7-19% of teeth that were initially vital were reported to have developed periapical pathology after tooth preparation and placement of complete coverage restorations over an observation of between 1-25 years (Karlsson, 1986; Jackson et al, 1992; Walton, 1999). Several authors have highlighted that more often than not, clinicians tend to over-prepare the tooth beyond the recommended preparation dimensions thus posing more risk of pulpal involvement (Nattress et al, 1995; Murphy et al, 2009; Davis et al, 2012). In an *in vitro* study, Davis et al (2012) performed microtomography scans of extracted teeth before and after crown preparation and analysed the distribution of remaining dentine thickness using three-dimensional colour-coded mapping software. The results revealed consistent over-preparation of the labio-proximal line angles. In a clinical setting this over-preparation may induce pulpal degeneration which is likely to compromise tooth and restoration longevity (Davis et al, 2012). A limitation of this study was that all the preparations were carried out by one operator, which might explain the consistent clinical error. Other studies however, also reported consistent over-preparation despite the use of multiple operators for preparations of extracoronal restorations (Nattress et al, 1995; Murphy et al, 2009).

Whilst there have been increasing reports on pulpal response and mechanisms of pulpal repair, there is currently a paucity of literature which reports the exact dimensions or the range of the width of enamel or dentine in unprepared teeth of varying morphology. Clinicians prepare teeth for restorations without knowing the dimensions of enamel and dentine thickness and therefore the proximity of the pulp to the prepared tooth surface. Dental radiographic views, more specifically bitewing radiographs, have been used to estimate the size of the pulp during tooth preparation. Chandler et al (2004), however, reported that pulp size had been underestimated in 23% of buccal views and 0.5% of mesial views taken with bitewings. This underestimation poses a risk of iatrogenic damage to pulp due to over-preparation.

A few studies have described the use of X-ray microtomography to determine the dimensions of remaining dentine thickness before and after tooth preparation (Elliot and Dover, 1982; Davis et al, 2012), in order to evaluate crown design to improve clinical outcomes. Davis et al (2012) acknowledged that clinicians have no means of establishing the dentine thicknesses of teeth before and after preparation. The study was able to identify the areas within dentine that were excessively prepared. They also reported a consistent over-preparation of the teeth along the labio-proximal line angle areas of the teeth, and a "tendency to leave considerably less than 2 mm residual dentine protecting the pulp, due to the proximity of the pulp horns in this region". This study, however, did not consider measuring the dimensions prior to preparation even though the authors acknowledged that due to this lack of information clinicians have no feedback. This is an important aspect in achieving optimal preparation quality and providing long-term treatment. An opportunity for the use of CBCT to assist in determining pre-treatment dimension of enamel and dentine prior to tooth preparation is therefore apparent.

CBCT settings can be manually manipulated. This implies that to use a specific CBCT unit for linear measurements, the unit must be calibrated in order to establish its level of accuracy and reproducibility. Therefore, when an object has its various dimensions measured using a conventional tool such as digital callipers; the dimensions can be compared with measurements obtained from the CBCT measuring software to determine the accuracy of the CBCT. Should there be a difference between the measurements obtained with each tool, that difference should be within a particular range of values, enabling a correction factor to be established.

Hence the rationale of this study was to determine the accuracy of a CBCT machine and therefore to provide a guideline for use in other CBCT machines. In addition, this would allow a much larger study to be conducted to determine internal tooth dimensions in different age cohorts.

CHAPTER 2. AIMS AND OBJECTIVES

The aim of this study was to compare linear measurements of tooth sections measured with digital callipers with those of the same tooth sections obtained with CBCT in order to calibrate and determine the accuracy of the CBCT machine.

The objectives were therefore to:

1. Use extracted teeth and section them at the planes which would most likely lead to the most tooth reduction during extra-coronal tooth preparations
2. Measure the thickness of both enamel and dentine using digital callipers accurate to 0.01mm
3. Mount these sections in a model and perform a CBCT scan
4. Determine the above-mentioned thicknesses using the CBCT software and to compare these with the calliper measurements. If the difference in the two measurements is considered to be of clinical significance a “correction factor” would need to be established.

Null hypothesis

There will be no statistically significant differences between the measurements acquired through digital callipers and those obtained through CBCT.

CHAPTER 3. MATERIALS AND METHODS

Prior to establishment of this research protocol, a pilot study with similar aims and objectives was conducted.

3.1 PILOT STUDY

Sixteen extracted permanent premolars and molars, which had been stored in sterile water, were obtained and subsequently embedded in a plaster matrix which was trimmed and shaped in a manner that simulated a jaw. The use of extracted teeth for both the pilot and the main study was covered under general ethical clearance M050760 and a waiver granted (reference number W-CJ-161012-1)

The criteria for their inclusion were that the teeth should be sound with no sign of any procedure having been performed on them.

A CBCT scan of the plaster matrix with the embedded teeth was performed and the measurements of enamel and dentine were taken at the following sites:

i) lingual cusp,

ii) buccal cusp,

iii) buccal bulge (the widest part of the tooth crown on the buccal surface of the tooth),

iv) lingual bulge (the widest part of the tooth crown on the lingual surface)

v) buccal margin position (a position of the buccal surface measured above the cementoenamel junction where the margin of a crown preparation can be placed),

vi) lingual margin position (a position of the lingual surface measured above the cementoenamel junction where the margin of a crown preparation can be placed)

vii) coronal width (the width of enamel and dentine that is measured at the central fossa of the tooth.

For the molars, the dimensions were recorded on both the mesial and distal aspects of each tooth.

Thereafter the teeth were sectioned through the buccal and lingual cusps in a buccolingual direction using hand piece-driven diamond wheels. The molars were sectioned at their mesial and distal aspects. Measurements of enamel and dentine were then taken at the same sites as for CBCT.

There were found to be significant and inconsistent differences between the measurements obtained with digital callipers and the CBCT software tool. This was surprising and was either due to inaccuracy of the CBCT or the manual measurements; or more likely, because the sectioning was not at the exact position of the CBCT plane.

Hence it was decided that the teeth should first be sectioned, and then mounted and scanned. This would enable precise positioning for the CBCT software to coincide exactly with the sectioned plane of the teeth.

3.2 MATERIALS AND METHODS

Sixteen extracted permanent premolars and molars, which had been stored in sterile water were sectioned in a buccolingual direction, using a hand piece-driven diamond wheel to expose the enamel and dentine. The tooth sections were numbered for identification, and then embedded in a typodont model.

Linear measurements of the enamel and dentine of each section were obtained using the digital callipers at the following sites:

1. The ideal position to place a margin during crown preparation on the lingual aspect which is described as the “lingual margin position” (LMP)
2. The widest/ most convex part of the tooth on the lingual side described as the “lingual bulge” (LB)
3. The highest point on the lingual cusp described as “lingual cusp” (LC)
4. The coronal aspect of the tooth in the central fossa regions described as “coronal”
5. The highest point on the buccal cusp described as “buccal cusp” (BC)
6. The widest/ most convex part of the tooth on the buccal side described as the “buccal bulge” (BB)
7. The ideal position to place a margin during crown preparation on the buccal aspect which was described as the “buccal margin position” (BMP)

A CBCT scan of the typodont model with the tooth sections was performed. The CBCT used was a Galileos unit (Galileos GAX 5 Compact, Sirona, Germany). The same linear measurements were obtained as with the digital callipers, using the digital linear measuring tool provided by the CBCT software. Both measurements (digital callipers and CBCT measuring tool) obtained for the enamel and dentine of each section were recorded in an Excel® spreadsheet and analysed for comparison.

Because individual measurements may be subject to variation, two operators performed the same measurements. The principal examiner had been trained and was experienced in the use of CBCT software as part of her postgraduate training. The second was a radiographer who utilised CBCT for patients on a daily basis. The operators were blinded from each other's measurements.

3.3 STATISTICAL ANALYSIS

Intra-Class Correlations were used to determine the inter-rater correlations. The Bland-Altman statistical analysis test was used to compare the two measurement techniques. This test quantifies the agreement between two different methods of measuring the same subject by analysing the mean difference and constructing limits of agreement.

Sample Size

Bland Altman analysis requires a sample size of at least 60 and preferably 100. Twenty-one tooth sections with their measurements provided 21x 7 x 2= 294 samples which proved to be more than adequate (Bland and Altman 1986). The number of sections that were used (21) was determined by the number of sections that the typodont model could accommodate.

3.4 LIMITATIONS

The study was limited to tooth sections of premolars and molars. Should the outcomes of the study suggest the application of a correction factor, the findings could only be applicable to the specific CBCT machine that was calibrated.

CHAPTER 4. RESULTS

4.1 INTRA-CLASS CORRELATIONS

In order to assess the reproducibility of the methods and the reliability of the measurements acquired by both evaluators, Intra-Class Correlations (ICC) were assessed (Table 1).

Table 1. Intra-Class Correlation across evaluators

	Intra Class Correlation	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	1000[a]	0,999	1,000	4237,781	293	293	0.000
Average measures	1000[b]	1000	1000	4237,781	293	293	0.000

[a] The estimator is the same, whether the interaction effect is present or not; [b] Type A correlation coefficients using an absolute agreement. df1= Degrees of freedom for single measures; df2=degrees of freedom for average measures.

The ICC yielded values of 0.999 thereby demonstrating high reliability and reproducibility of the measurements obtained from both raters (evaluators) The Standard Error of Measurement (SEM) approached 0, which was expected given the average ICC approaching unity.

4.1.1 Outlier

Within the 294 measurements, an outlier was observed as illustrated in Figure 1. The values are given in Table 2.

Table 2. Statistics for the outlier E1= Evaluator 1; E2 = Evaluator 2

E1 Callipers	E1 CBCT	E2 Callipers	E2 CBCT	Mean Callipers E1& E2	Mean CBCT E1 & E2	Diff mean
5,35	5,26	5,39	5,22	5,37	5,24	0,13

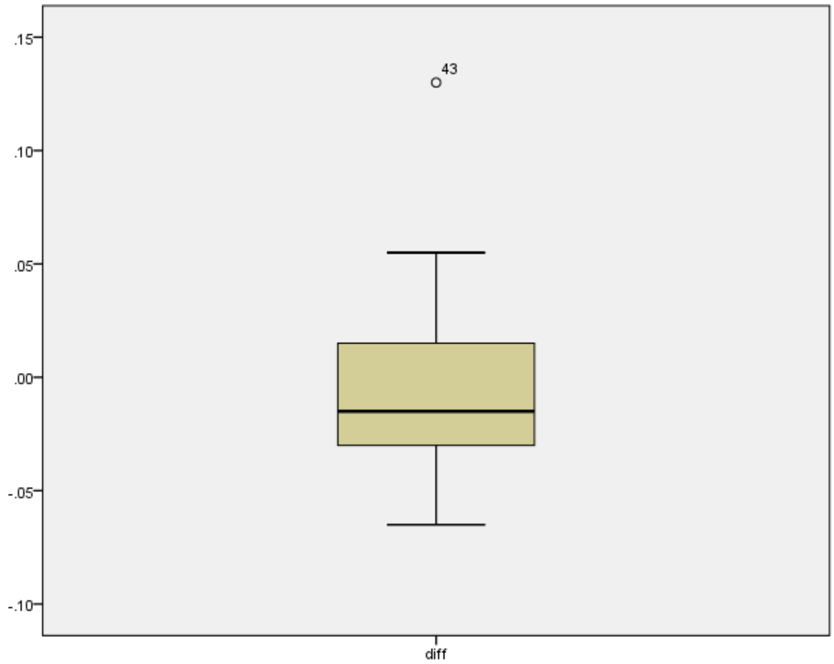

Figure 1. Box and Whisker plot including the outlier.

The outlier explains the reason for the inflation of the variability in the upper half of the plot; however, the remainder of the data fell within the upper and lower limits. It was therefore decided that this was an anomaly that could be excluded in subsequent analyses.

On re-calculating the ICC no difference was found in the correlations (Tables 3 and 4) and therefore further analyses could be conducted using the means of evaluator measurements.

Table 3. Total statistics for calliper readings; E1=evaluator 1, E2= evaluator 2

	Scale Mean if Outlier Deleted	**Scale Variance if Outlier Deleted**	**Total Correlation (Outlier deleted)**	**Squared Multiple Correlation**
Callipers (E1)	2,1887	1,072	1,000	0,999
Callipers (E2)	2,1883	1,065	1,000	0,999

Table 4. Total statistics for CBCT readings; E1=evaluator 1, E2= evaluator 2

	Scale Mean if Outlier Deleted	**Scale Variance if Outlier Deleted**	**Corrected Outlier-Total Correlation**	**Squared Multiple Correlation**
CBCT (E1)	2,1956	1,056	1,000	0,999
CBCT (E2)	2,1991	1,059	1,000	0,999

4.2 BLAND-ALTMAN ANALYSIS

4.2.1 Measurement differences

Tables 5 and 6 show the results from calculating the differences obtained between the calliper- and CBCT measurements of the means of the evaluators.

Table 5. Mean of evaluator differences between measurements methods

DIFFERENCE	n	percentage
Callipers< CBCT	181	61.6
Callipers =CBCT	8	2.7
Callipers >CBCT	105	35.7
TOTAL	294	100.0

Table 6. Mean and standard deviation

	N	Mean	Standard Deviation	Standard Error of Mean
Differences excluding outlier	293	-0.0094	0.02698	0.00158

The distribution of differences is shown in Figure 2. Although the distribution is not normal, the assumption of normality has to be made because of the large sample size, in line with the central limit theorem. Almost any test for significance will show differences, confirmed by the t-test statistics in Table 7.

Table 7. One-sample t-test statistics on the differences of measurements

	Test Value=0					
	t	Df	Sig (2-tailed)	Mean Difference	95 % Confidence Interval of the Difference	
					Lower Limit	Upper Limit
Differences	-5,933	292	0.000	0.00935	-0.0125	0.0062

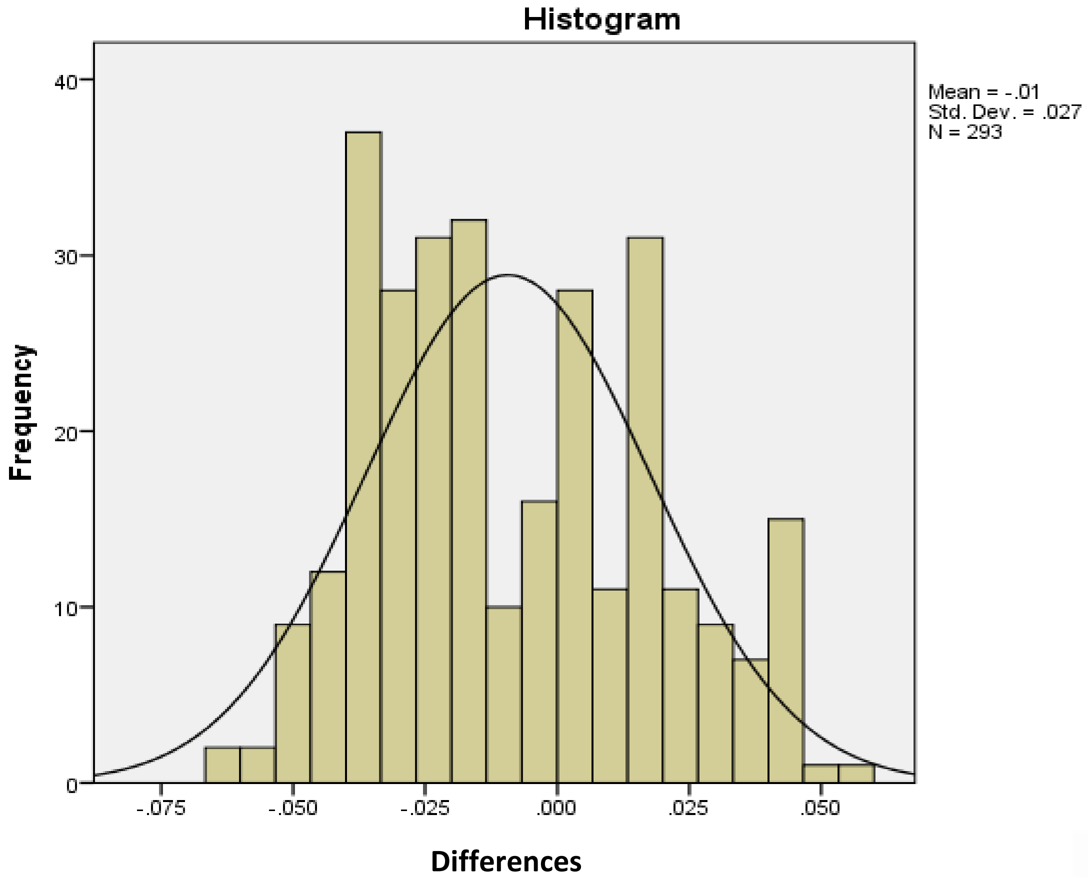

Figure 2. Frequency distribution plot of the mean differences between callipers and CBCT

4.2.2 Regression analysis

The linear regression analysis (Figure 3) demonstrated a positive linear relationship between the values obtained through callipers and CBCT. The correlation coefficient was 0.999 ($p<0.0001$, CI 0.001-0.007), indicating a high correlation.

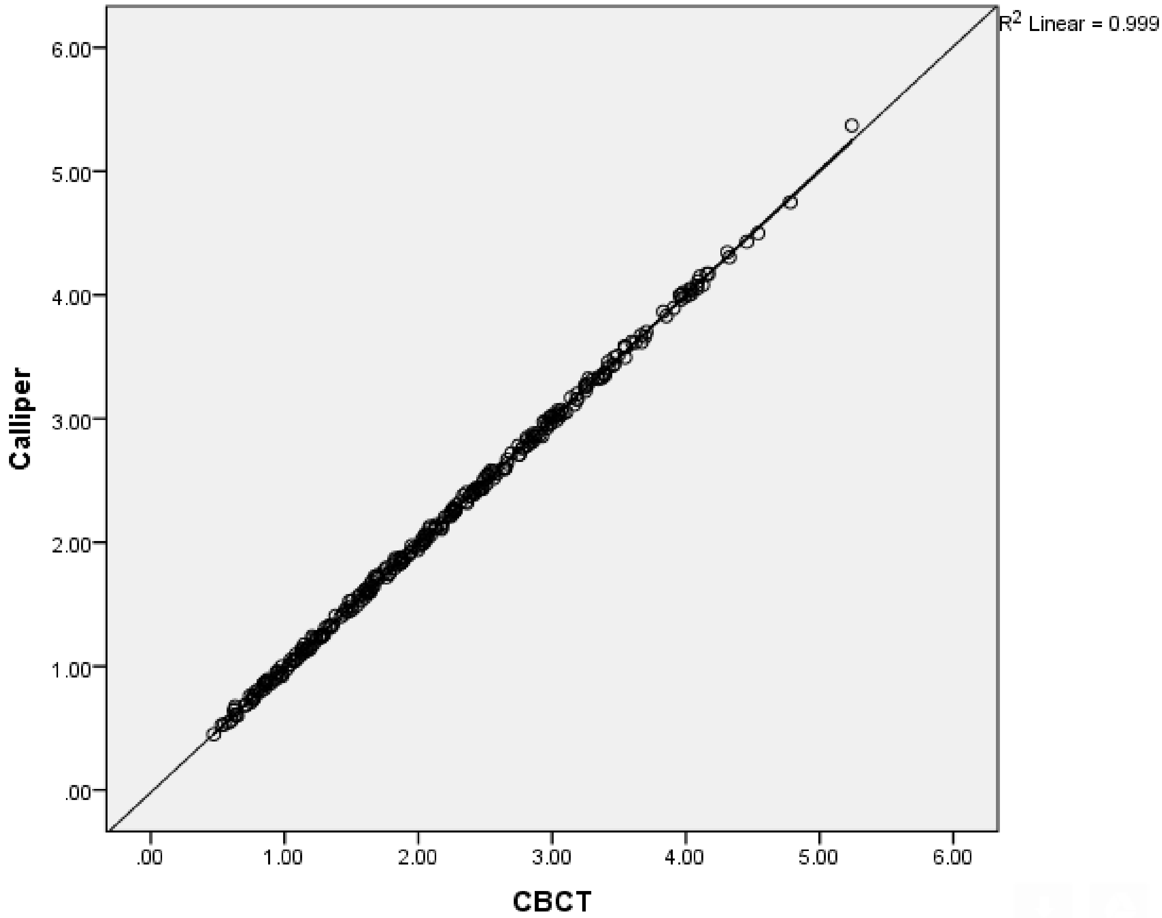

Figure 3. Linear regression plot of callipers versus CBCT

4.2.3 Bland-Altman analysis

A high correlation between methods does not necessarily translate into agreement between them and can be misleading. The Bland-Altman analysis evaluates the extent of the agreement between the methods by quantifying the limits of agreement. The agreement is found by plotting the results in a scatter plot of the differences against the mean, and expecting 95% of the differences to lie between ± 2 (more precisely 1.96) standard deviations of the differences (Giavarina 2015). This was found to be the case here. These values create the upper and lower limits of agreement and are shown as the horizontal lines above and below the line of the mean of the differences in Figure 4.

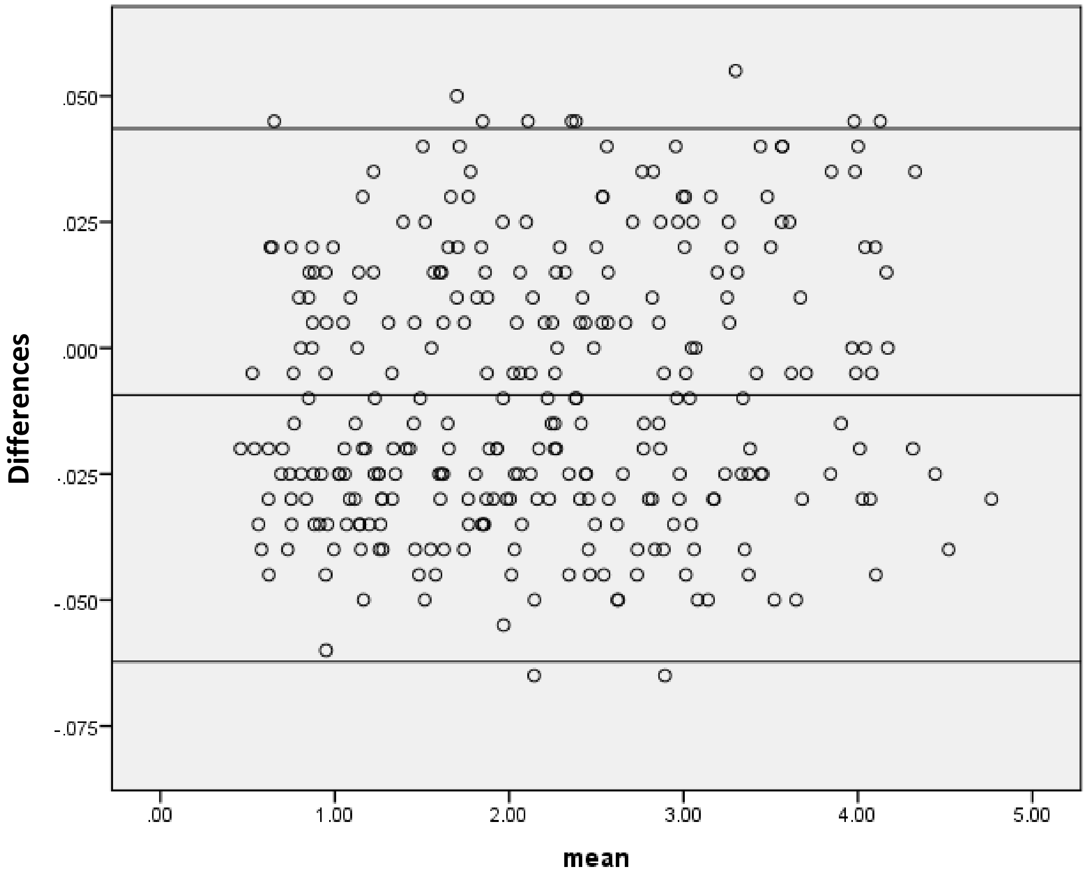

Figure 4. The Bland-Altman plot of the differences between the two methods (calliper and CBCT) plotted against the mean

The limits of agreement were -0.04mm and -0.140mm.

CHAPTER 5. DISCUSSION

The aim of this study was to determine the reliability and accuracy of the measurements of sectioned teeth obtained from the CBCT measuring software tool when compared with the same measurements made with digital callipers.

A pilot study using non sectioned teeth revealed significant and inconsistent differences between the above-mentioned measurements. Since the CBCT images were acquired before the teeth were sectioned, it could therefore not be established if the sectioning was made at the exact position of the points where the CBCT measurement was obtained. The sectioning may also have reduced the tooth structure thereby leading to incompatible readings. Hence it was decided that the teeth should be sectioned first and then mounted and scanned, as this would enable precise positioning of the CBCT software to coincide exactly with the sectioned plane of the teeth. Digital callipers and the CBCT software measuring tool were used by two evaluators to help confirm the validity of the method.

In order to determine the reliability between evaluators, an Intra Class Correlation Coefficient was calculated and a high correlation value of 0.999 was obtained.

An ideal outcome for the results obtained from both methods would be that they are identical. However, any method of measurement creates a degree of error. This may be related to the sample size or the correctness of execution of the procedures. In this study an outlier was observed. The outlier was excluded because in comparison to the mass of data the difference appeared to be abnormal. The analyses therefore excluded this outlier as it was one in 294 measurements, and the remaining 293 measurements in fact far exceed the requirements of the Bland-Altman test (Bland and Altman 1986).

The Bland-Altman analysis was used to quantify the agreement between the two types of measurements. It analyses the differences between the two measuring techniques and plots these against their means, as neither of the methods may be considered a "gold standard" method (Krouwer, 2008). In this case, the means of both evaluators could be pooled as the correlation between them was very high.

The descriptive statistics showed that the CBCT measurements were greater than for the digital callipers in about 60 percent of the readings for both evaluators. The mean of these differences, however was only 130µm. While studies have reported differences, (Hofmann et al, 2011; Baumgaertel et al, 2009), these studies were focused on tooth width measurements, rather than tooth substance measurements. Although these studies may be relevant for some aspects of dentistry such as orthodontics, they are of no value to the study of fixed prosthodontics as our interest is more focused on the dimensions of enamel and dentine in order to prevent pulpal insult. Brokos et al (2015) also focused on the dimension of tooth structure, but they measured only the enamel dimensions of anterior teeth and the influence of age changes on the enamel. Also, they did not compare CBCT to any other method. No other studies similar to this one have been reported; therefore no previous study exists with which these results can be compared.

The Bland-Altman analysis is valuable in that it constructs limits of agreement where measurements have clinical application as in this study. It is therefore important to quantify these limits and to interpret their clinical significance. In this study, these limits were found to be

-0.14mm and -0.04mm respectively. This means that the margin of error in tooth measurement between the two methods translates to a thickness of tooth enamel or dentine between 4 and 140μm of. In clinical terms, while text-books specify ranges of ideal tooth reduction, for example of 0.8mm (Shillingburg et al, 2012); those measurements in reality are almost impossible to replicate within 0.5mm. Coincidentally, the value of 0,5mm is the critical value or minimum width of residual dentine remaining after tooth preparation, at which histological changes in the dentino-pulpal complex can be observed, after a tooth has been subjected to some form of insult (Zach & Cohen, 1965; Seltzer& Bender, 1958, Stanley, 1994). As the differences observed between the two methods used in this study are much lower than this value, the two methods can be used interchangeably to measure tooth dimensions of enamel and dentine.

The overall differences in the measurements could have resulted from an error in the use of the measuring software tool or in the limitation of the CBCT to construct images of maximal accuracy. When measuring the widths of enamel and dentine the measurement sites are determined macroscopically with the aid of a computer mouse and then marked on the image. Differences in determining where to place the two points macroscopically in order to calculate the widths, may have caused differences between the two evaluators.

Predetermined settings for scanning and reconstruction may influence the quality of the image. An important factor is the voxel size. This influences the spatial resolution and the level of noise or scatter around the image of an anatomical structure, thereby affecting its clarity and visibility. The evaluators needed to determine visually the most mesial and distal points from the centre of the image from which to determine the measurement. It can therefore be established that the values obtained were subject to some level of human error even on a low scale. Sakabe et al (2007) highlighted the fact that discrepancies found when comparing CBCT to any other method of width measurement are inevitable due to the varying voxel size of each apparatus. Liang et al (2010) discovered, while comparing multi-slice computed tomography to CBCT measurements in dry skulls, that enamel and dentine were only moderately influenced by scanner type and field of view settings and conclude that this method was still acceptable. The supplier of the CBCT machine used in this study could not provide the evaluators with the voxel size.

As this study was limited to premolars and molars the implication of the results on anterior teeth is unknown. The extracted teeth were sectioned using diamond wheels and this process may have been destructive to the teeth. The two evaluators had both undergone a level of training in the use of CBCT software and digital callipers. The results may also highlight the impact of the level of training or expertise in order to achieve the highest level of correctness in the execution of the method. The impact of the level of experience in influencing the accuracy of measurements was reported by Radeke et al (2014).

It should be noted that the outcomes of this study are only applicable to the particular CBCT machine and cannot be generally applied to other machines even of the same make.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

Within the limitations of this study, the results obtained support the null hypothesis, and therefore CBCT technology can provide an accurate method for measuring the dimensions of enamel and dentine. This means that CBCT scans that have been obtained for other clinical purposes can be used to quantify enamel and dentine thickness prior to any invasive procedure such as tooth preparation for extra-coronal restorations. In addition, existing scans from different age cohorts can be used to provide a guide for average enamel and dentine thicknesses without requiring a CBCT scan. It is therefore recommended that further studies be undertaken to determine mean enamel and dentine thicknesses over a variety of age cohorts. The clinical implications of this are that the undesirable potential for iatrogenic damage due to over-preparation of teeth for extra-coronal restorations leading to failure of the restorations in the long term may be avoided. This concept may be simplified with the combined use of CAD-CAM technology which calculates the minimum thickness requirements of various ceramic materials. This may also have an impact on direct restorations where layering techniques of composite resins are utilised, particularly in the aesthetic zone.

In order for the application of this study to be more generally applicable, models of tooth sections from this study using different radio-opaque materials and representing all teeth may be created and used to calibrate any CBCT machine in the same manner, using only 100 measurements.

REFERENCES

al-Fawaz A, Gerzina TM, Hume WR. Movement of resin cement components through acid-treated dentin during crown cementation in vitro. J Endod. 1993; 19(5):219-223

Asgary S, Nikneshan S, Akbarzadeh- Bagheban A, Emadi N. Evaluation of diagnostic accuracy and dimensional measurements by using CBCT in mandibular first molars. J Clin Exp Dent 2016; 8(1): e1-8.

Baumgaertel S, Palomo J.M, Palomo L, Hans MG Reliability and accuracy of cone beam computed tomography dental measurements. Am J Orthod Dentofacial Orthop 2009; 136(1):19-28.

Benninger B, Peterson A, Cook V. Assessing validity of actual tooth height and width from cone beam images of cadavers with subsequent dissection to aid oral surgery. J Oral Maxillofac Surg. 2012; 70(2): 302-306.

Berco M, Rigali P, Miner M, DeLuca S, Anderson NK, Will LA. Accuracy and reliability of linear cephalometric measurements from cone-beam computed tomography scans of a dry human skull. Am J OrthodDentofacialOrthop.2009; 136(1):17.e1-9

Bland JM, Altman DG. Statistical method for assessing agreement between two methods of clinical measurement. Lancet. 1986; 327:307–310

Boeddinghaus R, Whyte A. Current concepts in maxillofacial imaging. Eur J Radiol 2008; 66(3):396–418.

Brokos YP, Stavridakis M, Bortolotto T, Krejci I. Evaluation of enamel thickness of upper anterior teeth in different age groups by dental cone beam computed tomography scan *in vivo*. Int J Adv Case Rep 2015; 2(23): 1396-1409

Chandler P, Ford TRP, Monteith BD. Pulp size in molars: underestimation on radiographs. J Oral Rehabil.2004; 31(8):764-769

Cohnen M, Kemper J, Mobes O, Pawelzik J, Modder U. Radiation dose in dental radiology. EurRadiol 2002; 12(3):634–637.

Davis GR, Tayeb RA, Seymour KG, Cherukara GP. Quantification of residual dentine thickness following crown preparation. J Dent. 2012; 40(7):571-576.

De Backer H, Van Maele G, De Moor N, Van de Berghe L, De Boever J. A 20-year retrospective survival study of fixed partial dentures. Int J Prosthodont 2006; 19(2):143-153

Dula K, Mini R, Lambrecht JT, van der Stelt PF, Schneeberger P, Clemens G, et al. Hypothetical mortality risk associated with spiral computed tomography of the maxilla and mandible. Eur J Oral Sci1996; 104(5-6):503–510

Elliot JC, Dover SD. X-ray microtomography. J Micros.1982; 126(Pt 2): 211-213

Ganguly R, Ramesh A, Pagni S. The accuracy of linear measurements of maxillary and mandibular edentulous sites in cone-beam computed tomography images with different fields of view and voxel sizes under simulated clinical conditions. Imaging Sci Dent 2016; 46(2): 93-101

Ge Z, Ma R, Li G, Zhang J, Ma X. Age estimation based on pulp chamber volume of first molars from cone beam computed tomography images. Forensic Sci Int 2015; 253:133.e1-133.e7.

Grunheid T, Patel N, De Felippe N, Wey A, Gaillard PR, Larson BE. Accuracy, reproducibility and time efficiency of dental measurements using different technologies. Am J Orthod Dentofacial Orthop 2014; 145(2):157-164.

Hatcher DC. Cone beam computed tomography: Craniofacial and airway analysis. Dent Clin North Am. 2012; 56(2):343-357

Honda K, Arai Y, Kashima M, Sawada K, Ejima K, Iwai K. Evaluation of the usefulness of the limited cone beam CT (3DX) in the assessment of the thickness of the roof of the glenoid fossa of the temporomandibular joint. Dentomaxillofac Radiol 2004; 33(6): 391-395

Jackson CR, Skidmore AE, Rice RT. Pulpal evaluation of teeth restored with fixed prostheses. J Prosthet Dent. 1992; 67(3):323-325

Joda T, Brägger U. Digital vs. conventional implant prosthetic workflows: a cost/time analysis. Clin Oral Implants Res.2015; 26(12):1430–1435

John GP, Joy TE, Mathew J, Kumar VRB. Applications of cone beam computed tomography for a prosthodontist. J Indian Prosthodont Soc 2016; 16(1): 3-7.

Karlsson S. A clinical evaluation of fixed bridges, 10 years following insertion. J Oral Rehabil. 1986; 13(3):423-432

Kiljunen, T, Kaasalainen T, Suomalainen A, Kortesniemi, M. Dental cone beam CT: A review. Physica Medica 2015; 31(8):844–860

Kim KD, Ruprecht A, Jeon K, Park CS. Personal computer-based three dimensional computed tomographic images of teeth for evaluating supernumerary of ectopically impacted teeth. Angle Orthod 2003; 73(5): 614-621

Krouwer JS. Why Bland-Altman plots should use X, not (Y+X)/2 when X is a reference method. Stat Med. 2008; 27(5):778-780.

Langeland K, Langeland LK. Pulp reactions to crown preparation, impression, temporary crown fixation, and permanent cementation. J. Prosthet Dent 1965; 15(1):129-134

Larheim TA, Abrahamsson A-K, Kristensen M, Arvidsson LZ. Temporomandibularjoint diagnostics using CBCT. Dentomaxillofac Radiol 2015; 44(1): 20140235.

Liang X, Jacobs R, Hassan B, Li L, Pauwels R, Corpas L et al. A comparative evaluation of cone beam computed tomography (CBCT) and multi slice CT (MSCT) Part 1. On subjective image quality. Eur J Radiol 2010; 75(2): 265-269

Moshfeghi M, Tavakoli A.M, Hosseini ET, Hosseini AT, Hosseini IT. Analysis of linear measurement accuracy obtained by cone beam computed tomography (CBCT-NewTom VG) Dent Res J (Isfahan).2012; 9(7): S57-S62

Mozzo P, Procacci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone beam technique. Preliminary results. Eur Radiol 1998; 8(9): 1558-1564.

Murphy F, McDonald A, Petrie A, Palmer G, Setchell D. Coronal tooth structure in root-treated teeth prepared for complete and partial coverage restorations. J Oral Rehabil 2009; 36(6):451-461

Murray PE, About I, Lumley PJ, Franquin JC, Remusat M, Smith AJ. Human odontoblast cell numbers following dental injury. J Dent 2000; 28(4):277-285.

Murray PE, Smith AJ, Windsor LJ, Mjor IA. Remaining dentine thickness and human pulp. Int Endod J. 2003; 36(1):33-43

Nattress BR, Youngson CC, Petterson CJW, Martin DM, Ralph JP. An in vitro assessment of tooth preparation for porcelain veneer restoration. J Dent 1995; 23(3):165-170

Nemtoi A, Czink C, Haba D, Gahleitner A. Cone beam CT: a current overview of devices. Dentomaxillofac Radiol. 2013; 42(8): 20120443

Pameijer CH1, Stanley HR, Ecker G. Biocompatibility of a glass ionomer luting agent. 2. Crown cementation. Am J Dent. 1991; 4(3):134-141.

Pontes EC, Soares DG, Hebling J, Costa CA. Cytotoxicity of resin-based luting cements to pulp cells. Am J Dent. 2014; 27(5):237-244

Qu X, Li G, Zhang Z, Ma X. Detection accuracy of in vitro approximal caries by cone beam computed tomography images. Eur J Radiol. 2011; 79(2):24–27

Radeke J, von Der Wense C, Lapatki BG. Comparison of orthodontic measurements on dental casts and 3D scans. J Orofac Orthop 2014; 75(4):264-274.

Sakabe J, Kuroki Y, Fujimaki S, Nakajima I, Honda K. Reproducibility and accuracy of measuring erupted teeth using limited cone beam X-ray CT. Dentomaxillofacial Radiol 2007; 36(1): 2-6

Sarment D. Three dimensional planning in the maxillofacial reconstruction of large defects using cone beam tomography: Oral and Maxillofacial Diagnosis and Applications. 1st ed USA: Wiley –Blackwell; 2014: 109-126.

Scaf G, Lurie AG, Mosier KM, Kantor ML, Ramsby GR, Freedman ML et al. Dosimetry and cost of imaging osseointegrated implants with film-based and computed tomography. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1997; 83(1):41–48

Scarfe WC, Farman AG, Sukovic P. Clinical applications of cone-beam computed tomography in dental practice. J Can Dent Assoc 2006; 72(1): 75-80

Scarfe WC, Farman AG. Cone beam computed tomography: a paradigm shift for clinical dentistry. Aust Dent Pract 2007; 45(5):102–110.

Scarfe WC, Farman AG. What is Cone-Beam CT and How Does it Work? Dent Clin N Am 2008; 52(4):707–730

Schulze DI, Heiland M, Thurmann H, Adam G. Radiation exposure during midfacial imaging using 4- and 16-slice computed tomography, cone beam computed tomography systems and conventional radiography. Dentomaxillofac Radiol. 2004; 33(2):83-86.

Seelbach P, Finger WJ, Ferger P, Balkenhol M. Temperature rise on dentin caused by temporary crown and fixed partial denture materials: influencing factors. J Dent. 2010; 38(12):964-973.

Seltzer S, Bender IB. Some influences affecting repair of the exposed pulps of dogs' teeth. J Dent Res 1958; 3(1):678-687

Shillingburg HT, Sather DA, Wilson EL, Cain JR, Mitchell DL, Blanco JL, Kessler JC. Fundamentals of Fixed Prosthodontics. 4thEdition.USA: Quintessence Publishing; 2012: 347f

Stanley HR. Dental iatrogenesis. Int Dent J.1994; 44(1):3-18

Valderhaug J, Jokstad A, Ambjornsen E, Norheim PW. Assessment of the periapical and clinical status of crowned teeth over 25 years. J Dent 1997; 25(2):97-105.

Veyre-Goulet S, Fortin T, Thierry A. Accuracy of linear measurements provided by cone beam computed tomography to asses bone quantity in the posterior maxilla: a human cadaver study. Clin Implant Dent Related Res 2008; 10(4): 226

Walton J, Gardner F, Agar. A survey of crown and fixed partial dentures failures: Length of service and reason for replacement. J Prosthet Dent 1986; 56:416-421

Walton TR. A 10-year longitudinal study of fixed prosthodontics: clinical characteristics and outcome of single -unit metal-ceramic crowns. Int J Prosthodont 1999; 12(6):519-526.

Wenzel, A. Digital radiography and caries diagnosis. Dentomaxillofac Radiol. 1998; 27(1):3-11

Worthington P, Rubinstein J, Hatcher DC. The role of cone-beam computed tomography in the planning and placement of implants. J Am Dent Assoc 2010; 141 Suppl 3: 19S- 24S.

Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol.1965; 19:515-530.

APPENDIX 1. Ethical Clearance

Human Research Ethics Committee (Medical)

Research Office Secretariat: Senate House Room SH10005, 10th floor. Tel +27 (0)11-717-1252
Medical School Secretariat: P V Tobias Health Sciences Building, 2nd floor
Tel +27 (0)11-717-2700 / 1234 / 1252 / 2656
Private Bag 3, Wits 2050, www.wits.ac.za. Fax +27 (0)11-717-1265
South African National Health Research Ethics Council registration: REC-250208-04
United States Office of Human Research Protections registration: FWA00000715 IRB00001223

Ref: W-CJ-160120-1 20/01/2016

TO WHOM IT MAY CONCERN:

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical).

Investigator: **Dr T I Mmutlana (student no 699045)**

Project title: **Establishing the biological basis for tooth preparation dimensions in the fabrication of extracoronal restorations.**

Reason: This is a laboratory study using extracted teeth. There are no human particpants.

UNIVERSITY OF THE WITWATERSRAND
OFFICE OF THE DEPUTY VICE CHANCELLOR RESEARCH
20 JAN 2016
RESEARCH OFFICE
HREC (Medical)
JOHANNESBURG

Professor Peter Cleaton-Jones

Chair: Human Research Ethics Committee (Medical)

Copy – HREC (Medical) Secretariat: Zanele Ndlovu, Rhulani Mkansi.

APPENDIX 2. Turnitin report

Submission Info

SUBMISSION ID	790088690
SUBMISSION DATE	27-Mar-2017 04:21PM
SUBMISSION COUNT	1
FILE NAME	Peter_Owen_00000240...
FILE SIZE	47.83K
CHARACTER COUNT	29449
WORD COUNT	5452
PAGE COUNT	22
ORIGINALITY	
OVERALL	3%
INTERNET	0%
PUBLICATIONS	3%
STUDENT PAPERS	0%
GRADEMARK	
LAST GRADED	27-Mar-2017
COMMENTS	0
QUICKMARKS	0