Accuracy and reliability of traditional measurement techniques for tooth widths and arch perimeter compared to CAD/CAM.

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A mini-thesis submitted in partial fulfilment of the requirements for the degree of MSc in Paediatric Dentistry.

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KEYWORDS

Accuracy

Arch perimeter

CAD/CAM

Digital model

Plaster model

Tooth widths

ABSTRACT

Background: Plaster models form an integral part of the traditional orthodontic records. They are necessary for diagnosis and treatment planning, case presentations as well as for the evaluation of treatment progress. The accuracy of the measurements taken for space assessment is crucial prior to treatment planning. The introduction of digital models overcomes some problems experienced with plaster models. Digital models have shown to be an acceptable alternative for plaster models.

Aim: The aim of the study was to determine the accuracy of traditional measurement techniques when compared to the CAD/ CAM measurements in the assessment of tooth widths and arch perimeter from plaster models.

Method: The mesio-distal tooth widths and arch perimeter of thirty archived plaster models were measured using a digital caliper to the nearest 0.01 mm and divider to the nearest 0.1 mm. Corresponding digital models were produced by scanning them with a CAD/CAM (InEos X5) and space analysis completed by measurements using InEos Blue software. Measurements were repeated after 1 week from the initial measurement. The methods were compared using descriptive analysis (mean difference and standard deviation).

Results: The operator reliability was high for digital models as well as the plaster models when the measurement tool was the digital caliper (analyzed using the Pearson correlation coefficient in the paired t-test). The mean values of tooth widths measurements of CAD/CAM, digital caliper and divider were 6.82 (±0.04), 6.94 (± 0.04) and 7.11 (± 0.04). There was a significant difference between the measurements made by the CAD/CAM and the divider. Additionally significant differences between the measurements by digital caliper and divider measurements ($p < 0.05$) were observed. No significant difference was found when comparing CAD/CAM to digital caliper. Positive correlation was displayed between CAD/CAM, digital caliper and the divider, but the measurements completed with the digital caliper had the highest correlation with the CAD/CAM. The difference was not significant between the aforementioned measurement tools ($p > 0.05$). Arch perimeter measurements showed

no statistical significant difference between CAD/CAM, digital caliper and divider ($p < 0.05$).

Conclusion: Archived plaster models stored as records can be converted to digital models as it will have the same accuracy of measurements. The value of doing a space analysis with the CAD/CAM system can be performed with similar reliability on the digital models as a caliper on plaster models.

DECLARATION

I, the undersigned, Mona Elmubarak, hereby declare that the work contained in this dissertation titled; "Accuracy and reliability of traditional measurement techniques for tooth widths and arch perimeter compared to CAD/CAM." is my original work and has not been previously in its entirety or in any part submitted at any university for any degree or examination.

Mona Elmubarak

May 2018

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- **Mr Leo Dingemans** Inlab Product Specialist & Sales manager
- **Clayton Johnson** Laboratory technician
- **Mr Ahmed Eldud** statistician

DEDICATION

I would like to dedicate this dissertation to my role models my parents; ***Salah Elmubarak*** and ***Kawther Mohamed,*** for their unconditional love and endless support all the way throughout my journey.

To my husband; ***Dr Omer Ahmed***, who has been a constant source of support and encouragement, I am truly thankful for having you in my life.

To the apple of my eye, my daughter **Farah**, whom inspired me and gave me the necessary strength to complete my postgraduate degree, you are a true meaning of happiness.

Thank you

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

In orthodontic cases, plaster models are necessary for diagnosis and treatment planning, case presentations as well as for the evaluation of treatment progress (Okunami *et al.,* 2007). Plaster models provide a three dimensional view of the patients occlusion. This makes it possible for the clinicians to evaluate any malocclusion from more vantage points than the clinical examination alone (Quimby *et al.,* 2004). Thus, these plaster models form an integral part of the traditional orthodontic records.

Plaster models have been used in different ways starting from general inspection of the cast to taking direct measurements using dividers, gauges or digital calipers (Goonewardene *et al*., 2008). Model analyses play a major role in orthodontic diagnosis and treatment planning (Leifert *et al.,* 2009). Taking measurements for space assessment is a crucial step prior to treatment planning of malocclusion cases and therefore the accuracy of the measurements will impact on the space analysis. Several space analysis methods are available to the clinician, including those of Black (1902), Howes (1947), Neff (1949), Bolton (1958) and Wheeler (1966). Measurements from plaster models are derived from the fabrication of the model preceded by an impression of the patient's dentition. The traditional methods of obtaining measurements are done by using manual devices such as dividers and calipers (Redlich *et al.,* 2008). Despite having limitations when measuring crowded and rotated teeth, these aforementioned methods are considered to be the 'gold standard' when evaluated against newer methods of measuring such as photocopies of study models and sonic digitization (Champagne, 1992; Mok and Cooke, 1998; Quimby *et al.,* 2004).

Three-dimensional study models were introduced to overcome some problems experienced with plaster models (Redmond, 2001), such as the time required for taking impressions, fabricating the models, the risk of physical damage and the vast amount of space required for storage (Jacob *et al.,* 2015). Also, plaster model analysis can be time-consuming when it is done manually compared to digital methods (Zilberman *et al.,* 2003). Computerized methods were more time-efficient especially in a busy practice (Tomassetti *et al.,* 2001). The introduction of digital models has shown to be an acceptable alternative for plaster model (Santoro *et al.*, 2003).

CHAPTER 2: LITERATURE REVIEW

2.1 Digital models

Many attempts have been made for the conversion of plaster models into 3-dimensional virtual models (El-Zanaty *et al.,* 2010). Since the mid-1990s, the technology of scanning has been available, however, software developers have redefined and modified this approach over the past 5-6 years. Digital technology has become integrated in practices, so as to improve efficiency and quality of clinical services (Okunami *et al.*, 2007). The rise of this modern digital technology provides several options to be considered for orthodontists in everyday practice. A study by Rheude *et al* (2005) assessed the effect of digital models compared to plaster models in orthodontic decision-making, diagnosis and treatment planning (Rheude *et al.*, 2005). There were minor changes recorded and the results showed that digital models can be used successfully for orthodontic records (Rheude *et al.*, 2005).

Recently, various companies have developed different technologies to produce digital models by using alginate impressions and then the subsequent scanning of the plaster model (Moreira *et al.*, 2014). Other diagnostic methods to obtain measurements that have been investigated include the use of photos, holograms and computer-aided digitization (Leifert *et al.*, 2009). From all the methods, digital models can be produced directly from oral structures via an intra-oral scanner. The computer software then digitizes the information to render a digital model of the teeth, oral structure and occlusion which provides the most practical solution (Jacob *et al.*, 2015).

A systematic review by Fleming *et al* (2011) was done to reach a conclusion whether plaster models can be replaced by digital models. Previous studies have concluded that digital software is accurate and can reproduce accuracy of dental features (Mullen *et al.*, 2007; Fleming *et al.*, 2011). Advantages of digital models include the rapid access to digital information, easy transfer of data and, reduced storage requirements. The limitation experienced with the gold standard method of direct measurements with rulers or calipers carry an inevitable degree of inaccuracy and clinician error. Quimby *et al* (2004) had an attempt to produce a more accurate gold standard with accurate measurements using computer-based models produced by OrthoCAD system (Quimby *et al.*, 2004). Quimby *et al* (2004) tested the accuracy, reliability and the efficacy of measurements done using digital models. They concluded that measurements on digital models can be used sufficiently by the clinician. This provides adequate information to be used for treatment planning (Quimby *et al.*, 2004).

In conclusion, digital models will not make an orthodontist diagnose or plan the treatment of malocclusion differently from that of plaster models, digital models have been found to be a clinically acceptable replacement for plaster models when performing routine measurements in orthodontic practices. However, this thesis will illustrate an additional feature for the use of digital models for space analysis versus plaster models.

2.2 Accuracy of digital model measurements

As elluded to previously traditional measurements made on plaster models are accounted as the 'gold standard' (Goonewardene *et al.*, 2008). Comparative studies to test reproducibility, accuracy and efficacy of measurements generated by computer-based models yielded acceptable results compared to plaster models. The differences were statistically insignificant however they were clinically insignificant and acceptable (Tomassetti *et al.*, 2001; Mayers *et al.*, 2005; Moreira *et al.*, 2014). For example, Stevens and colleagues (2006) supported the use and accuracy of digital models in measurements more than those from plaster models due to caliper design having limited accessibility to the landmarks (Stevens *et al.*,2006). The precise difference between digital and plaster models; cannot be standardized due to the various computer software at each platform (Akyalcin *et al.*, 2013). Regardless, a three dimensional view makes it possible to allow for measurements to take place.

Jacob *et al* (2015) evaluated the validity and reliability of extra-oral and two intra-oral scanners. Dry mandibles with a full complement of teeth were used. Measurements were taken of the molar width/height, canine width/height, and premolar diameter. The results showed high reliability of all measurements taken by the three scanners with minimum error (Jacob *et al.*, 2015).Also; they concluded that there were no differences between measurements taken directly from dry mandibles and measurements from extra-oral and intra-oral scanners. These findings support other studies which showed that the digital models produced with extra-oral and intra-oral scanners were valid and highly reliable, compared to the direct measurements on plaster models, thus making them clinically acceptable (Stevens *et al.*, 2006; Leifert *et al.*, 2009; Fleming *et al.*, *2011*).

2.2.1 OrthoCAD Technology

OrthoCAD technology, which is a 3D imaging software programme, allows the models to be utilized, stored, viewed and managed (Joffe, 2014). It was first designed to overcome the problems with traditional study models and to allow the use of a full electronic record for the patient. OrthoCAD models have many advantages over plaster models such as being simpler and more effective in measuring, easy storage and retrieval with other clinical data of patients. The only disadvantage was that they cannot be articulated and mounted to simulate patient's temporomandibular joint function and being difficult to handle models (Joffe, 2014).

A study by Santoro *et al* (2003) has also shown further favourable results when evaluating the reliability of the OrthoCAD system when measuring tooth widths and overbite. It showed statistical significant differences, and that the digital models were an acceptable alternative to plaster models for routine measurements used in orthodontic practice. Digital models produced by OrthoCAD and its software were more reliable to use in analysing arch length discrepancies. This depends on the orthodontists training with the digital software (Santoro *et al.*, 2003). Furthermore, Leifert *et al* (2009) compared space analysis obtained from digital models and plasters models. The accuracy of the software for space analysis evaluation using digital models turned to be clinically acceptable (Leifert *et al.*, 2009).

2.2.2 Teledent software

Other technologies were also tested for accuracy; Redlich *et al* (2008) assessed the reliability of Teledent, a computerized software which offers new means of space analysis, using cross section planes which serves like arms of digital caliper (Redlich *et al.*, 2008). When compared with the digital caliper, thirty cast models of mixed and permanent dentitions were scanned with a three dimensional (3D) holographic sensor and two types of digital measurements were taken. The study showed that the use of cross sectional planes for the measurements of arch length and tooth widths did not differ from caliper measurements on plaster models. So it can be of use clinically. Also, measurements taken in the cross section planes were found to be more precise than the linear measurements in crowded dentition. As for the linear measurement, the results were clinically acceptable in uncrowded and mildly crowded dentitions only (Redlich *et al.*, 2008).

2.2.3 Digitization method

There was limited research to ascertain the accuracy of scanned models, thus, research have indicated that the measurements obtained from digital models can be accepted in comparison with plaster models (Joffe, 2004).

On the other hand, one of the studies did not have favourable results when comparing the reproducibility of arch perimeter and mesiodistal tooth widths values on plaster models given by caliper and DigiGraph Workstation (Mok and Cooke, 1998). This sonic digitization method which was originally used for measuring lateral cephalometric values, arch perimeter discrepancy and mesio-distal tooth width, have resulted in variations and overestimations in some of the measurements. This method should be interpreted carefully as its clinical usefulness in evaluating the space problem of a patient malocclusion is still questioned (Mok and Cooke, 1998).

One of the diagnostic tools used in orthodontics is Bolton tooth-size analysis. This is done by individual measurement of maxillary and mandibular teeth and calculating a ratio that indicates an inter-arch tooth-size discrepancy for a good occlusion (Bolton, 1958). In a study by Tomassetti *et al* (2001) a comparison between measurements of Vernier caliper and three computerized programs which are ; Quickceph, OrthoCAD and Hamilton Arch Tooth System (HATS) was done. Results revealed difference in time needed to finish the analyses where Quickceph was the fastest of all. However, there was no statistically significant difference between all these methods with Bolton analysis when the Vernier caliper was used (Tomassetti *et al.*, 2001).

2.2.4 Emodel software

Stevens *et al* (2007) also compared standard plaster models with the digital models made with Emodel software for tooth size analysis and occlusal relationships. Digital models reproducibility made via concordance correlation coefficient, turned out to be excellent in most cases (Stevens *et al.*, 2007). Another study by Mullen *et al* (2007), Emodel software was used in calculating Bolton ratio in comparison to digital caliper (Mullen *et al.*, 2007). They concluded that the measurement was more accurate and faster than digital caliper that was used with plaster models (Mullen *et al.*, 2007).Therefore, digital models produced by Emodel software can be used for orthodontic diagnostic purposes (Akyalcin *et al.*,2013).

2.2.5 Computer Tomography (CT) scan

Furthermore, El-Zanaty *et al* (2010) tested how accurate was a 3D-based dental measurement programme that used scans by computer tomography. The obtained result was then compared with measurements made manually with calipers on plaster models. This comparison was made by the following dental arch measurements: mesio-distal tooth width, arch lengths, arch widths, palatal depth and arch perimeter. There was excellent agreement between both methods in most of the results, although it was difficult to identify the exact contact points of adjacent teeth in addition to operators' skills. These were the reasons of fair agreement in some results (El-Zanaty *et al.,* 2010). However, the critical issue was scanning the patients in order to only measure their teeth whereas other studies used models and impression scans. In other words, radiation necessity and patients benefit and risks should be of high concern.

2.2.6 Cone Beam Computed Tomography (CBCT)

Cone Bean Computed Tomography imaging has been assessed for its reliability and accuracy in dental measurements (Kau *et al.*, 2010). Periago *et al* (2008) concluded in their study that there was a significant difference when comparing the accuracy of craniofacial landmarks measurement with measurements taken with digital caliper (Periago *et al.,* 2008). However, this difference was clinically acceptable (Periago *et al.,* 2008). Other studies also agreed that the level of accuracy of CBCT was similar to other digital model techniques in the comparison of linear measurements (Creed *et al.,* 2011: Akyalcin *et al.,* 2013; Tarazona *et al.,* 2013). On the other hand, de Waard *et al* (2014) reported relevant differences and questioned the reliability of CBCT when producing 3D models (de Waard *et al.,* 2014). CBCT images were less accurate than digital models obtained from intraoral scanners (de Waard *et al.,* 2014; Rossini *et al.,* 2016).

2.3 CAD/CAM technology

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology have been used both in the dental laboratory and dental office for the past 25 years (Duret *et al.,* 1988). This equipment can scan, mill and design devices, which are applied in the fabrication of inlays and onlays, crowns, fixed partial dentures, veneers and even full-mouth reconstruction (Davidowitz & Kotick, 2012).

CAD/ CAM has been used in orthodontics in the manufacturing of Invisalign, which involves a series of clear removable appliances. This offers an aesthetic alternative to fixed orthodontic appliances (Melkos, 2005). High precision CAD/CAM was used to define lingual retainers to optimize their position, shape and contact with teeth. The retainer was strongly adapted to teeth (Wolf *et al.*, 2015).Thus improving patient comfort and the retentive effect (Wolf *et al.*, 2015). In addition, CAD/CAM is used in the fabrication of customized brackets and arch wires for lingual orthodontic treatment and titanium Herbst appliances (Wiechmann *et al.*, 2003).

2.3.1 Accuracy of CAD/CAM

The use of a digital method to produce crown and bridge crowns over conventional method helped to decrease the chance of laboratory technician errors. There are many laboratory mistakes that can be overcome with CAD/CAM over conventional crown fabrication (Jonathan *et al.*, 2014). The accuracy of the Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies for crown and bridge applications are greatly needed when it comes to producing prosthetic restorations (Beuer *et al.*, 2008). Compared to manually-produced crown restorations, CAD/CAM has a superior advantage of a standardized production guided by the computer software (Tinschert *et al.*, 2000). The marginal fit and adaptation is an important component for clinical success. In order to produce an efficient restoration with a long term survival rate, the marginal adaptation has to be accurate (Moldovan *et al.*, 2011). Also, the marginal adaptation of prosthetic restoration made by CAD/CAM depends on the quality of the three dimensional image produced (Tapie *et al.*, 2015).

CAD/CAM can produce a marginal fit to a tolerance of 10-50 µm (Trinschert *et al.*, 2001; Bindl and Mörmann, 2005; Reich *et al.*, 2005). Currently, there are different types of CAD/CAM systems available. Several studies were done to assess the accuracy of the CAD/CAM systems in marginal adaptation using different dental materials (Moldovan *et al.*, 2011; Hamza *et al.*, 2013). A study by Jonathan *et al* (2014) compared the marginal fit of crowns fabricated conventionally and digitally (Jonathan *et al.*, 2014). The marginal fit was assessed by measuring the vertical marginal gap. This is because the vertical marginal gap allows for the evaluation of the crown margin (Jonathan *et al.*, 2014). Results showed that the marginal gap was significantly smaller using the digital method (CAD/CAM) than the conventional method. However, both fell within the limits of clinically acceptable crown margins (Jonathan *et al.*, 2014). The Cerec system (Sirona Dentsply, Germany) has been shown to be extremely accurate for the marginal adaptation and fit in many studies since its induction (Luthardt *et al.*, 2005; Trifkovic *et al.*, 2014; Bohner *et al.*, 2017).

2.3.2 CAD/CAM scanning

The Cerec system (Sirona Dentsply, Germany) is one of the most frequently used CAD/CAM systems, which offers both intra-oral and extra-oral scanning (Trifkovic *et al.,* 2014).

Their method of digitization is based on active triangulation (Budak *et al.,* 2012). However, the measuring performances by Cerec have improved significantly by implementing a new lens system and blue light –emitting diode (LED) light. This light provides more accurate measurement (Trifkovic *et al.,* 2014).

When evaluating the measuring performances of a 3D digitization method, accuracy and precision are of the main indicators (Trifkovic *et al.,* 2014). A study by Luthardt *et al* (2005) concluded that extra-oral scanners using Cerec 3D camera showed higher accuracy than intraoral scanner (Luthardt *et al.,* 2005). This was also agreed in a study by Trifkovic *et al* (2014), were results showed high accuracy of Cerec InEos Blue surface digitization device while no significant difference when the device was compared to Cerec AC (Trifkovic *et al.,*2014). Furthermore, Bohner *et al* (2017) have evaluated the intraoral and extra-oral scanners for the purpose of image quality. Two of Sirona scanners were included in this study CEREC Bluecam intra-oral scanner and Cerec inEos X5 extra-oral scanner. There was no significant difference between the scanners as they showed similar accuracy in scanning (Bohner *et al.,* 2017). Also, the trueness of the scans of inEos X5 was agreed in a study by Kirsch *et al* (2017) compared to other Sirona systems and producing the smoothest scans (Kirsch *et al.,* 2017; Yee *et al.,* 2018).

2.4 Motivation for the study

There was slight difference in some measurements of digital models from those obtained from plaster models in the previous studies. Digital models produced from alginate impressions or plaster model scans were proven to be reliable and accurate and can be used for orthodontic treatment planning sufficiently (Moreira *et al.,* 2014). Many comparative studies have evaluated measurements reliability obtained by the digital models from plaster models (Zilberman *et al.,*2003; Okunami *et al.,* 2007; Leifert *et al.,*2009; Akyalcin *et al.,* 2014), but there were no studies that used CAD/CAM to measure tooth size and space assessment. Rossini *et al* (2016) concluded in a review with high level of evidence that digital models can be as reliable as plaster models with high accuracy and reproducibility (Rossini *et al.,* 2016). Moreover, they can be considered as the new gold standard in current clinical practice (Rossini *et al.*, 2016). As a new method, clinical acceptance must be assessed by comparing it with the traditional methods taken manually on plaster models. Thus, the aim of this study is to determine the accuracy of the traditional techniques when compared to CAD/CAM measurements in assessing tooth widths and arch perimeter from plaster models. The hypotheses were as follows:

1. The CAD/CAM measurements were more accurate than measurements done by divider and digital caliper from plaster models.
2. The null hypothesis was that there is no difference between measurements made on digital models scanned with CAD/CAM and those made on plaster models using divider and digital caliper.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Aims and objectives

The main aim of the study was to determine the accuracy of traditional measurement techniques when compared to the CAD/ CAM measurements in the assessment of tooth widths and arch perimeter from plaster models**.**

The objectives of the study were:

- To measure tooth widths and arch perimeter with divider and digital caliper.
- To measure tooth widths and arch perimeter using Sirona inEos Blue (CAD/CAM).
- To compare measurements obtained with divider, digital caliper and Sirona inEos Blue (CAD/CAM).
- To develop a correction coefficient of the buccal segment to use with digital caliper and divider based on the tooth width readings obtained from the CAD/ CAM in the premolar region.

3.2 Research design

This research is a comparative assessment between direct measurements of plaster study models with divider and digital caliper versus the measurements obtained on CAD/CAM of the same study models.

3.3 Ethical considerations

Approval to conduct the study was sought from the University of the Western Cape Biomedical Research Ethics Committee (Project Registration Number BM/16/3/27). Permission to access the archives of Orthodontics department was obtained from CEO/Dean of the faculty Prof. YI Osman. No personal patient information was recorded; the plaster models were assigned by numbers only, thus preserving patient anonymity.

3.4 Study sample

The study sample consisted of thirty pairs of randomly selected diagnostic study models (upper and lower), from the archives of the Orthodontic Department at University of the Western Cape.

3.4.1 Inclusion criteria

The criteria for inclusion into the study included study models with teeth that are in good condition i.e. no un-restored cavities, interproximal/occlusal attrition and no chipped or broken teeth. The study models that were chosen had full complement of permanent teeth from first permanent molar to contralateral first permanent molar of both upper and lower models i.e. 16 to 26 and 36 to 46.

3.4.2 Exclusion criteria

Study models that were excluded in this study were those with primary teeth and partially erupted permanent teeth.

3.5 Sample size

A statistician was consulted to assist with an estimation of the sample size. Looking at the literature and comparative studies and based on previous studies, the average number of models was 30.

3.6 Data collection technique

3.6.1 Measurement of tooth widths and arch perimeter

In order to maintain the clinical relevance of tooth size determination, each tooth was measured by the greatest mesio-distal diameter from the anatomic mesial contact point to the anatomic distal contact point. This was determined by way of visual interpretation of tooth morphology.

The arch perimeter of each maxillary and mandibular model was measured in four segments as follows: A- from the mesial contact point (below marginal ridge) of one first permanent molar along the central fissures/line of occlusion to the distal tip of the lateral incisor, B- from the lateral incisor to the midline. C- from midline to distal tip of lateral incisor, D- lateral incisor to contralateral first permanent molar (below mesial marginal ridge) as per the Figure 3.1 and 3.2.

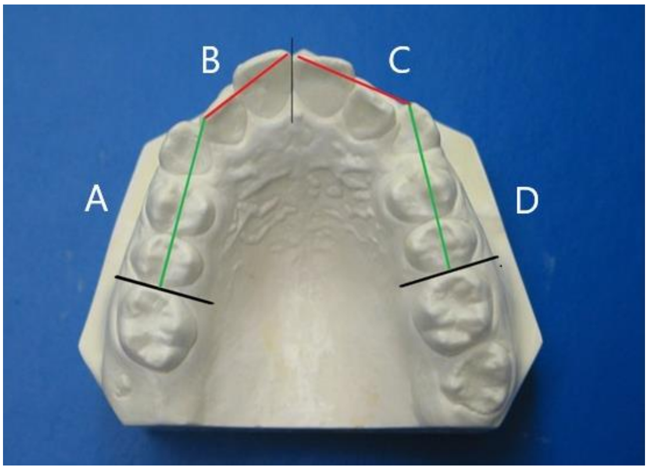


Figure 3.1 Arch perimeter determination (in four segments) in plaster model using digital caliper and divider.

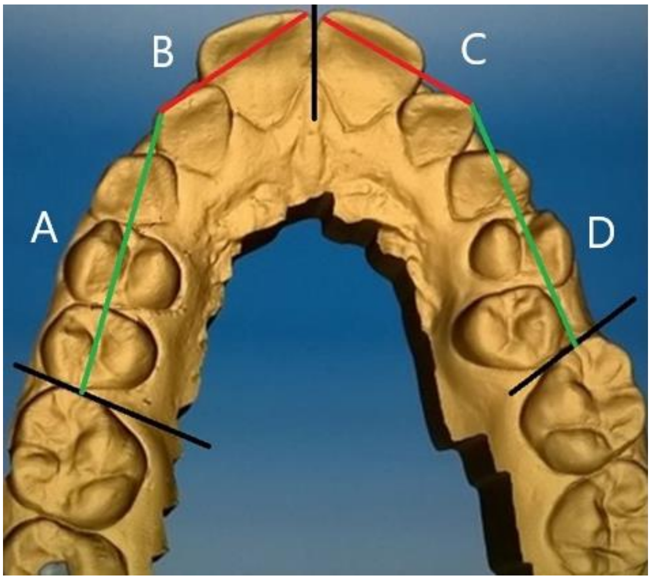


Figure 3.2 Arch perimeter determination (in four segments) on digital model using CAD/CAM

3.6.2 Measurement of individual tooth widths for correction coefficient

In order to calculate the correction coefficient of the buccal segment, the premolar region measurement made by digital caliper and divider was assessed and compared to the CAD/CAM measurements. The sum of the measured tooth widths of the two premolars in each quadrant was used to develop a correction coefficient.

3.6.3 Methods of measurement

The measurements were done in plaster and digital models by the researcher.

3.6.3.1 Digital models

The study models were taken to Sirona Dentsply Company headquarters in Cape Town to be scanned on the Sirona CEREC Inlab inEos X5 (Sirona-Dentsply Dental Systems, Germany) , in order to be digitized and to obtain a digital file. The image was produced based on digital stripe projection with blue light. The inEos X5 have the advantage of scanning automatically as well as manually. The full automatic scanning mode is done using the rotation arm with a universal holder that allowed the high quality camera to capture a number of teeth per image. This benefit in saving time while scanning all the models compared to the manual scan used in Sirona inEos Blue that was available in dental laboratory, Faculty of Dentistry, University of the Western Cape. Furthermore, the technology used in inEos X5 allows the standardization of images with high accuracy and eliminates any user error during the imaging process Figure 3.3.

Prior scanning, a Cerec Optispray was applied on all study models in a very light layer to allow for precise and accurate detailed image as shown in Figure 3.4 and 3.5. The plaster casts were secured onto the robotic arm and scanned individually. The scanner captured multiple images in order to create the digital model. The plaster models were articulated so that the buccal surface was scanned in all directions.

The digital models were then transferred to Sirona inEos Blue software (inLab Version 16.1.0.81747 Sirona Dental Systems, South Africa) and were measured using the distance tool. For ease and accuracy of measurements, the images were enlarged on screen as needed. As for severely mal-positioned teeth, the images were rotated on screen and enlarged from the occlusal view for better visibility. The pointers were located at the greatest mesio-distal points in the tooth using the distance tool for tooth width measurement as shown in Figure 3.6. The arch perimeter was also measured in four segments as shown in Figure 3.7.

Figure 3.3 Sirona inEos X5 scanner

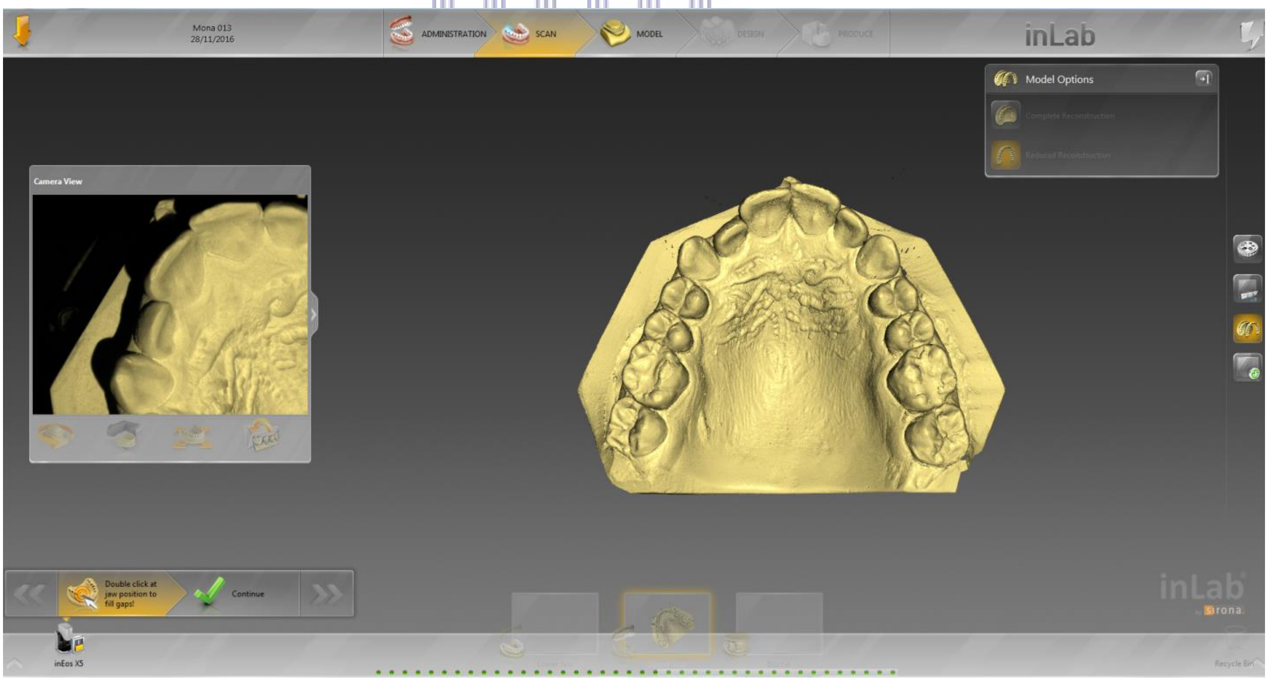


Figure 3.4 Three-dimensional view of digital model (upper) (by Sirona inEos X5)

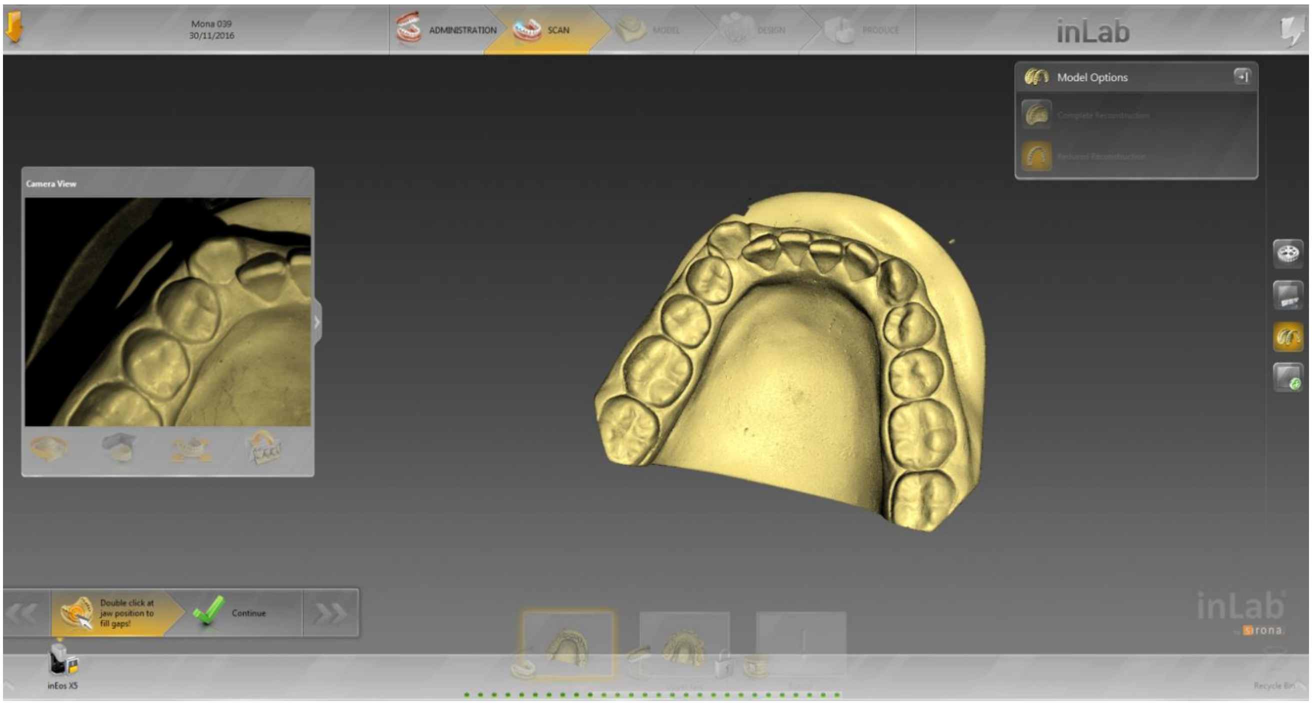


Figure 3.5 An example of a digital model (lower) (by Sirona inEos X5)

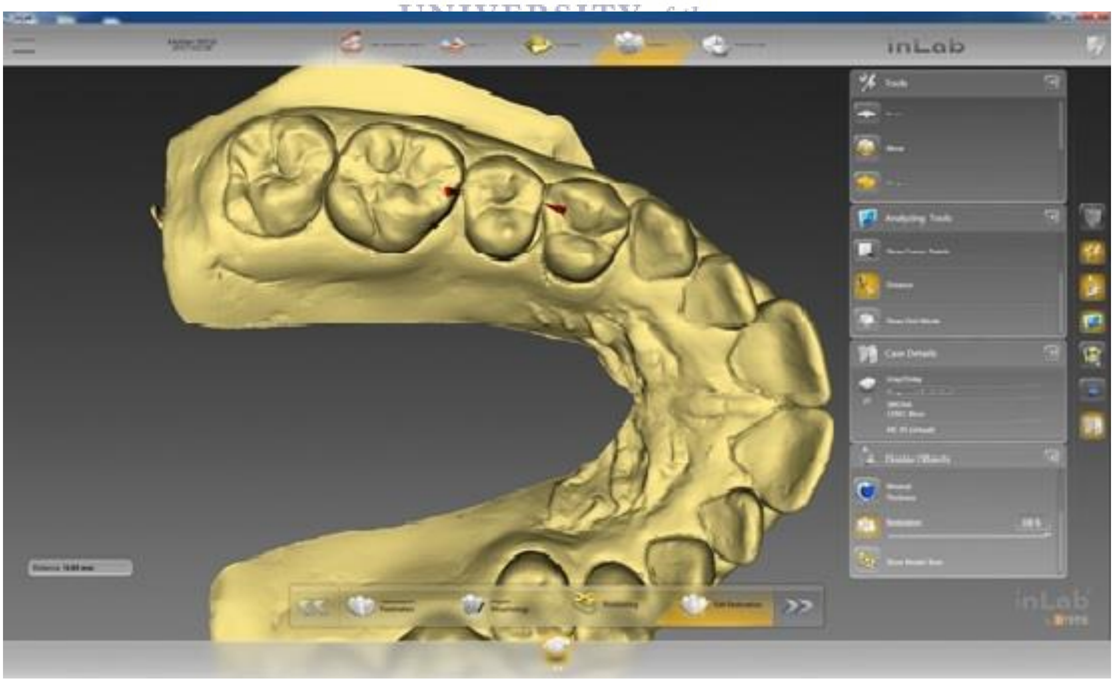


Figure 3.6 Mesio-distal tooth width measurement with Cad/Cam software (by Sirona inEos Blue)

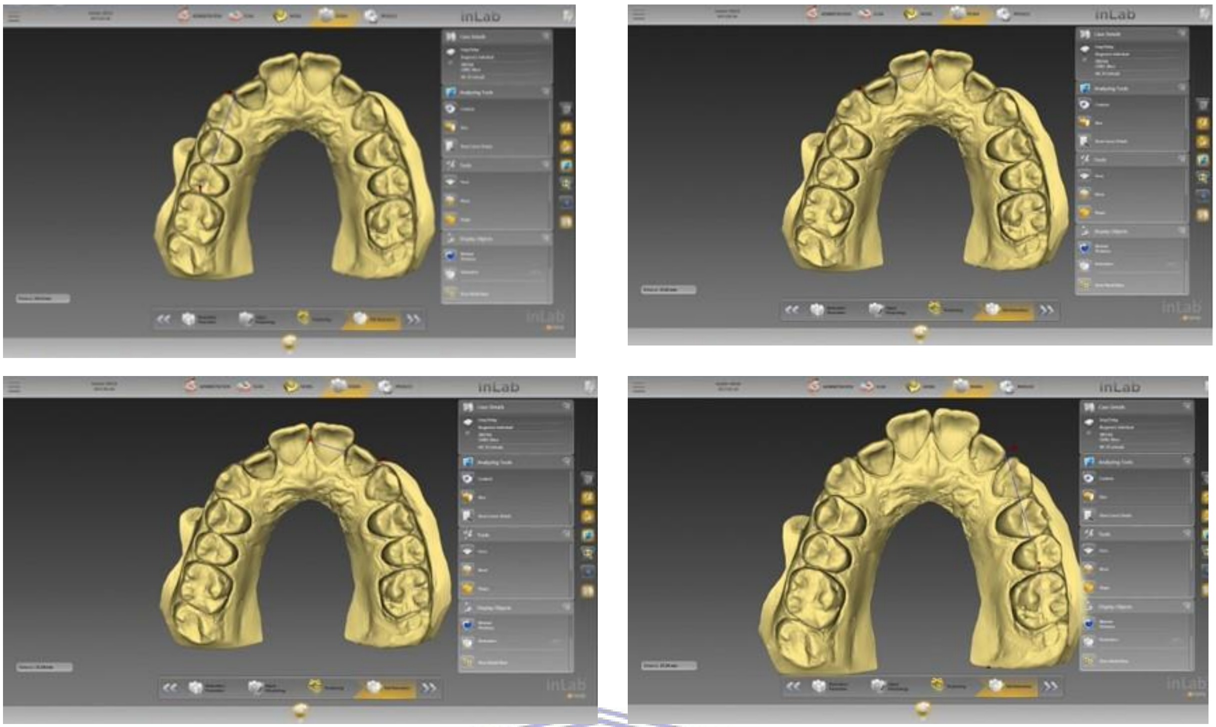


Figure 3.7 Arch perimeter measurement done in four segments (by Sirona inEos Blue).

3.6.3.2 Digital caliper

The plaster models were measured manually using a hand held electronic digital caliper (Fowler NSK MAX-CAL, serial number 265842, Japan) with an accuracy of 0.01mm. The mesio-distal width of each tooth was measured at its greatest width, by holding the caliper perpendicular to the occlusal plane of the tooth (Figure 3.8 and 3.9). The arch perimeter measurements were taken directly mesial of permanent first molar to distal tip of lateral incisor and from distal tip of lateral incisor to midline. The same areas were completed in the opposite side.

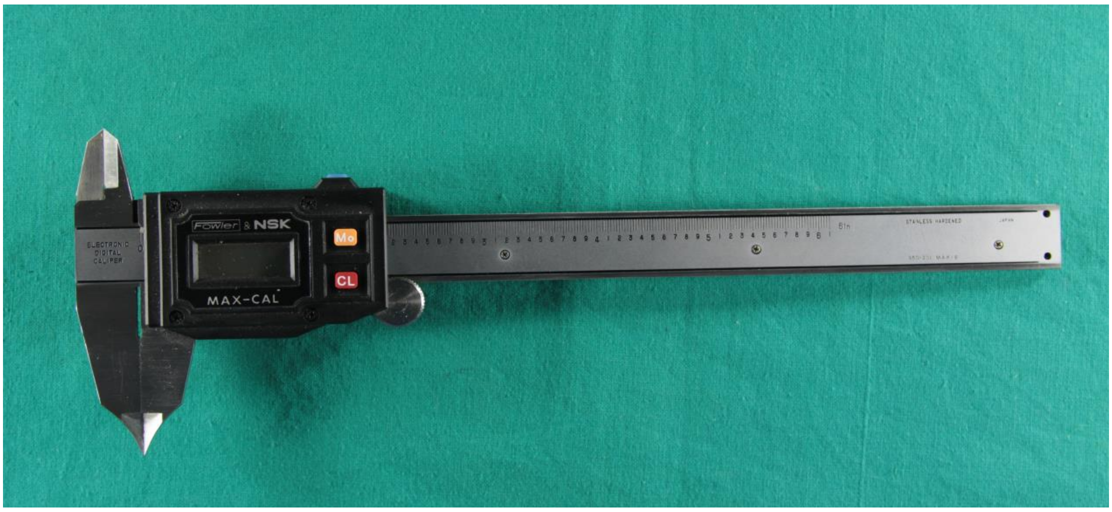


Figure 3.8 Electronic digital caliper

Figure 3.9 Measurement of plaster model with digital caliper

3.6.3.3 Divider

Direct measurements were made from the plaster models using the divider for mesio-distal diameter of teeth and transferred to a ruler as shown below in Figure 3.10 and 3.11. Likewise, the arch perimeter measurements were taken directly mesial of permanent first molar to distal tip of lateral incisor and from distal tip of lateral incisor to midline. The same areas were completed in the opposite side. Measurements were recorded to the nearest 0.1 mm.

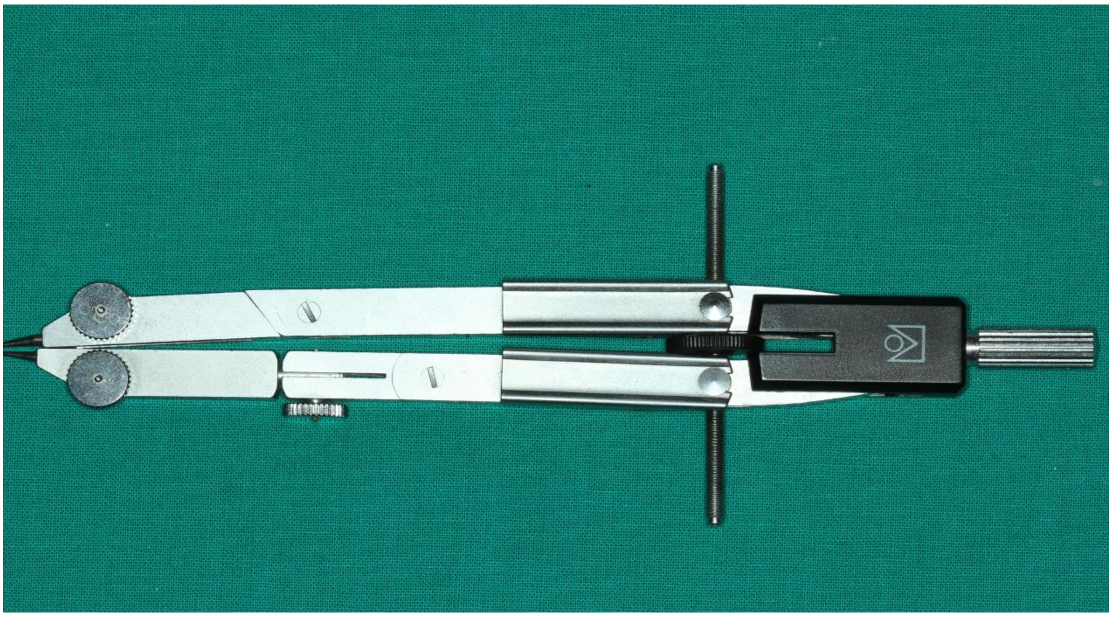


Figure 3.10 A divider

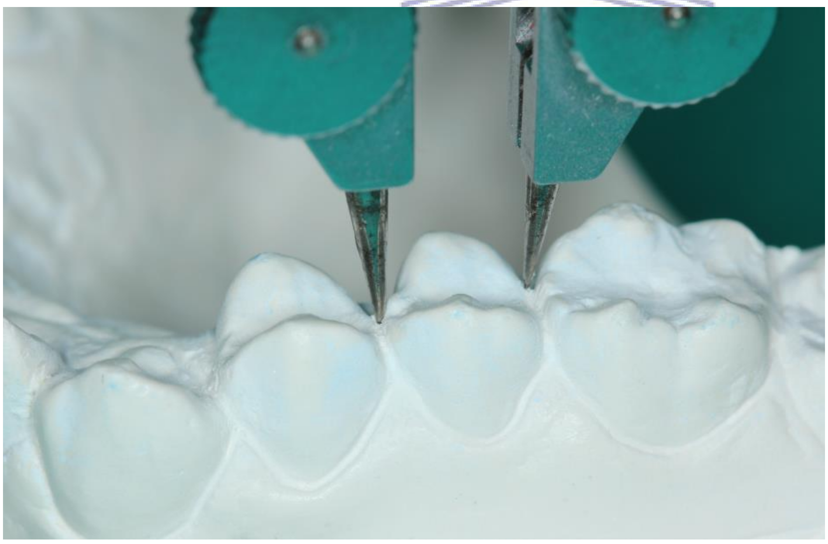


Figure 3.11 Measurement of plaster model with divider

3.7 Pilot study

A pilot study was carried out on 5 plaster models and digital models that were scanned using Sirona inEos Blue in March 2016, with the help of a co-supervisor (RM). The purpose of this process was to test the feasibility of the measurements and refine the methodology for reproducibility in dental practice.

3.8 Operator reliability

Calibration was done with repeated measurements at least a week apart using 10 sets of randomly selected plaster models and their digitized images. Reliability was estimated by calculating the observed error variance using paired differences.

3.9 Statistical Analysis

All measurements were recorded on a Microsoft Excel spreadsheet (Microsoft, Redmond, WA, USA) and analysed using SPSS Statistics V25.0. The operator reliability was tested by t-test paired two sample whereas the multiple comparisons between the methods was done using Tukey's HSD (honestly significant distance) test.

Since no study has been published on the device used for this study, Sirona inEos Blue, the estimated standard deviation and mean difference were based on average values of similar studies (Fleming *et al.*, 2011).

Accuracy evaluation

The accuracy of the tested methods in this study was defined by the smallest difference between measurement techniques. The greater the discrepancy between the measurements the less accurate the technique.

In this study, the linear measurements made in clinically relevant directions (mesio-distal tooth widths and arch measurements) between the 3 methods were compared.

CHAPTER 4: RESULTS

4.1 Operator reliability

The operator reliability was assessed by re-measuring 10 randomly selected digital and plaster models, one week after the initial measurements. The statistical analysis was done using two-sample t-test. The Kappa test was not used because the data in this study was numerical rather than categorical. The analysis was as follows for tooth widths and arch perimeter measurements:

4.1.1 Tooth widths measurements

The number of observations in the 10 models was a total of 200 readings; this includes 10 teeth in the upper models and 10 teeth in the lower models.

Table 4.1 Measurements (in millimetres) using Sirona inEos Blue (CAD/CAM)

	CAD/CAM (initial)	*CAD/CAM (repeated)*
Mean (mm)	6.95	6.93
Variance	0.94	0.95
Observations	200	200
Pearson Correlation	0.96	
Hypothesized Mean Difference	0	
df	199	
t Stat	1.16	
P(T<=t) one-tail	0.12	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.25	
t Critical two-tail	1.97	

Table 4.2 Measurements using the digital caliper

	Digital caliper (initial)	*Digital caliper (repeated)*
Mean (mm)	7.04	7.07
Variance	1.14	1.02
Observations	200	200
Pearson Correlation	0.92	
Hypothesized Mean Difference	0	
df	199	
t Stat	-0.95	
P(T<=t) one-tail	0.17	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.34	
t Critical two-tail	1.97	

Table 4.3 Measurements using the divider

	Divider (initial)	*Divider (repeated)*
Mean (mm)	7.21	7.14
Variance	0.99	0.95
Observations	200	200
Pearson Correlation	0.92	
Hypothesized Mean Difference	0	
df	199	
t Stat	2.45	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.02	
t Critical two-tail	1.97	

4.1.2 Arch perimeter measurements

The number of observations was 80 for the 10 models, i.e. 4 segments in the upper models and 4 segments in the lower models.

Table 4.4 Measurements using Sirona inEos Blue (CAD/CAM)

	CAD/CAM (initial)	***CAD/CAM (repeated)***
Mean (mm)	18.12	18.03
Variance	29.23	30.04
Observations	80	80
Pearson Correlation	0.99	
Hypothesized Mean Difference	0	
df	79	
t Stat	0.93	
P(T<=t) one-tail	0.18	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.35	
t Critical two-tail	1.99	

Table 4.5 Measurements using the digital caliper

	Digital caliper (initial)	***Digital caliper (repeated)***
Mean (mm)	18.03	18.24
Variance	30.50	28.74
Observations	80	80
Pearson Correlation	0.99	
Hypothesized Mean Difference	0	
df	79	
t Stat	-2.60	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.66	

P(T<=t) two-tail	0.01
t Critical two-tail	1.99

Table 4.6 Measurements using the divider

	Divider (initial)	***Divider (repeated)***
Mean (mm)	17.96	18.35
Variance	31.48	28.20
Observations	80	80
Pearson Correlation	0.98	
Hypothesized Mean Difference	0	
df	79	
t Stat	-3.38	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.00	
t Critical two-tail	1.99	

4.2 Comparison of tooth widths measurements between Sirona inEos Blue (CAD/CAM), digital caliper and divider

Table 4.7 Descriptive statistics and results of the statistical analysis of the tooth widths measurements in millimetres (mm) performed using CAD/CAM, digital caliper and divider.

Measurement	N	Mean (±SE)	Standard Deviation	95% Confidence Interval for Mean		Minimum	Maximum
				Lower Interval	Upper Interval		
CAD/CAM	600	6.82 (±0.04)	0.94	6.75	6.90	4.30	9.83
Digital caliper	600	6.94 (± 0.04)	0.99	6.86	7.01	4.44	9.94
Divider	600	7.11 (± 0.04)	0.95	7.04	7.19	4.50	10.00

N = the number of tooth widths readings in all sample size.

SE= standard error

Table 4.8 Multiple comparisons between CAD/CAM, digital caliper and divider for tooth widths measurements

Measurement		Mean Difference (±SE)	p-value	95% Confidence Interval	
				Lower Interval	Upper Interval
CAD/CAM	**Digital caliper**	-0.12 (±0.06)	0.09	-0.25	0.01
	Divider	-0.29 (± 0.06)	0.00	-0.42	-0.16
Digital caliper	**CAD/CAM**	0.12 (± 0.06)	0.09	-0.01	0.25
	Divider	-0.18 (± 0.06)	0.01	-0.31	-0.04
Divider	**CAD/CAM**	0.29 (± 0.06)	0.00	0.16	0.42
	Digital caliper	0.18 (± 0.06)	0.01	0.04	0.31

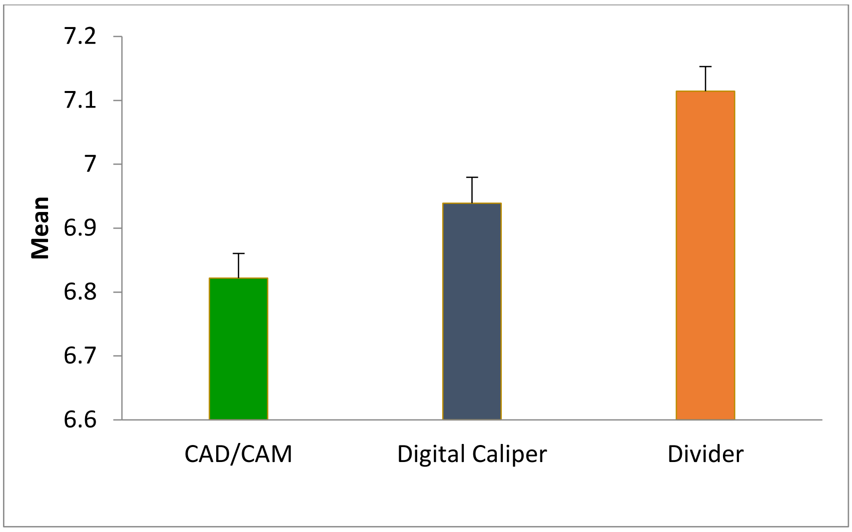


Figure 4.1 Mean values of CAD/CAM, digital caliper and divider with standard errors.

4.2.1 Correlations between CAD/CAM, digital caliper and divider:

Table 4.9 Correlations between CAD/CAM, digital caliper and divider

Correlations				
		CAD/CAM	**Digital caliper**	**Divider**
CAD/CAM	**Pearson Correlation**	1	0.95	0.91
	Sig. (2-tailed)		0.00	0.00
	N	600		
Digital caliper	**Pearson Correlation**	0.95	1	0.93
	Sig. (2-tailed)	0.00		0.00
	N	600		
Divider	**Pearson Correlation**	0.91	0.93	1
	Sig. (2-tailed)	0.00	0.00	
	N	600		

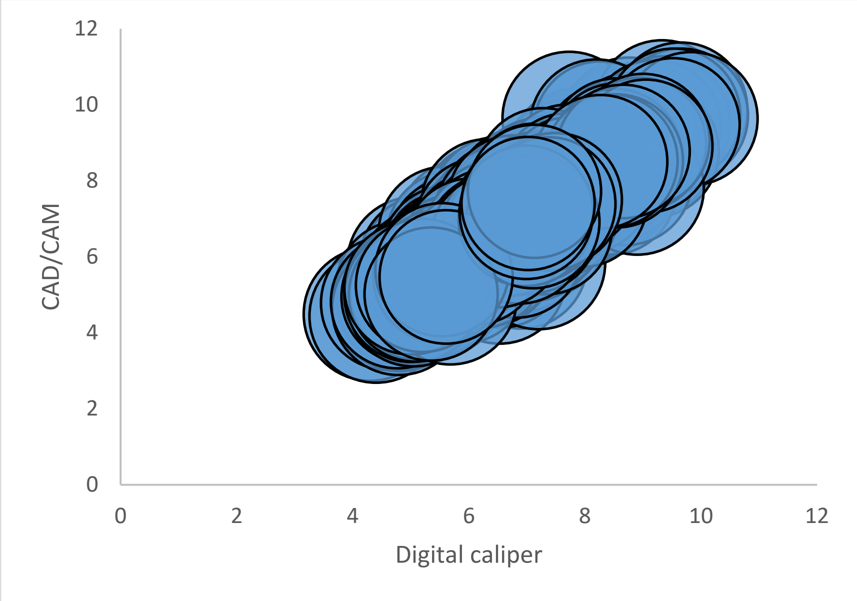


Figure 4.2 The correlation between CAD/CAM and digital caliper

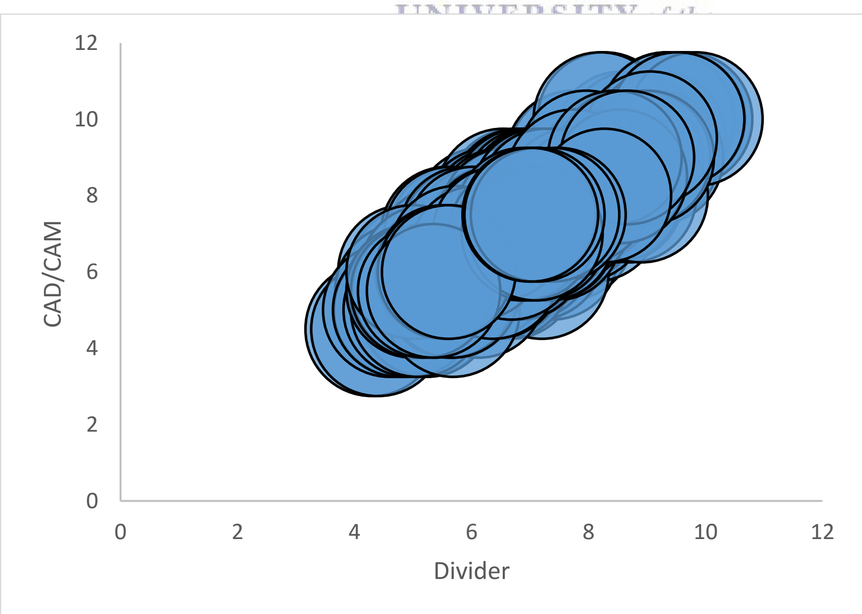


Figure 4.3 The correlation between CAD/CAM and divider

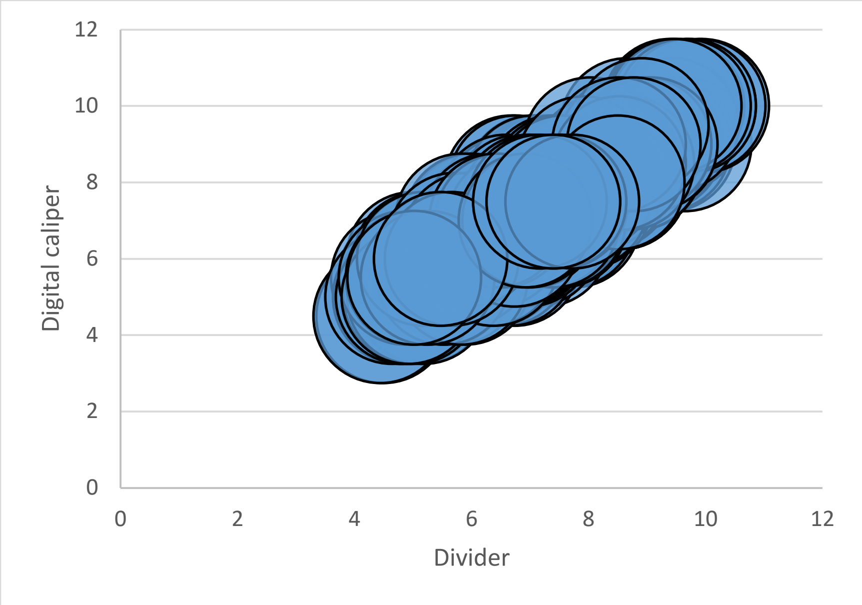


Figure 4.4 The correlation between digital caliper and divider

The Pearson's Correlation investigates the relationship between two quantitative, continuous variables, for example, CAD/CAM and digital caliper/divider. Pearson's correlation coefficient (r) is a measure of strength of the association between these two variables. A linear and positive correlation between the two variables is present. The figures 4.2, 4.3, 4.4 indicate that the strength of association between the variables assessed are very high with CAD/CAM to digital caliper (r=0.95) and CAD/CAM to divider (r=0.91) (Table 4.9).

The t-test is used to establish if the correlation coefficient is significantly different from zero and hence there is evidence of an association between the two variables. Therefore the correlation coefficient is very highly significantly different from zero ($p < 0.001$).

4.3 Comparison of arch perimeter measurements between CAD/CAM, digital caliper and divider

4.3.1 Comparison of arch perimeter individually measured in four segments:

A) Upper models

Table 4.10 Descriptive statistics and results of the statistical analysis of the arch perimeter measurements in millimetres (mm) for upper models performed using CAD/CAM, digital caliper and divider.

Segment	**Measurement**	**Mean (±SD)**	**95% Confidence Interval for Mean**		**p-value**
			Lower Interval	**Upper Interval**	
UA	**CAD/CAM**	23.81 (± 0.25)	23.31	24.32	0.85
	Digital caliper	23.91 (±0.27)	23.37	24.45	
	Divider	24.02 (±0.25)	23.50	24.53	
UB	**CAD/CAM**	14.97 (±0.22)	14.53	15.41	0.31
	Digital caliper	14.66 (±0.24)	14.18	15.14	
	Divider	14.43 (±0.29)	13.84	15.03	
UC	**CAD/CAM**	14.74 (±0.22)	14.29	15.20	0.97
	Digital caliper	14.73 (±0.21)	14.30	15.16	
	Divider	14.80 (±0.23)	14.32	15.28	
UD	**CAD/CAM**	23.89 (± 0.26)	23.36	24.43	0.95
	Digital caliper	23.97 (±0.30)	23.36	24.58	
	Divider	23.83 (±0.30)	23.21	24.45	

SD = standard deviation

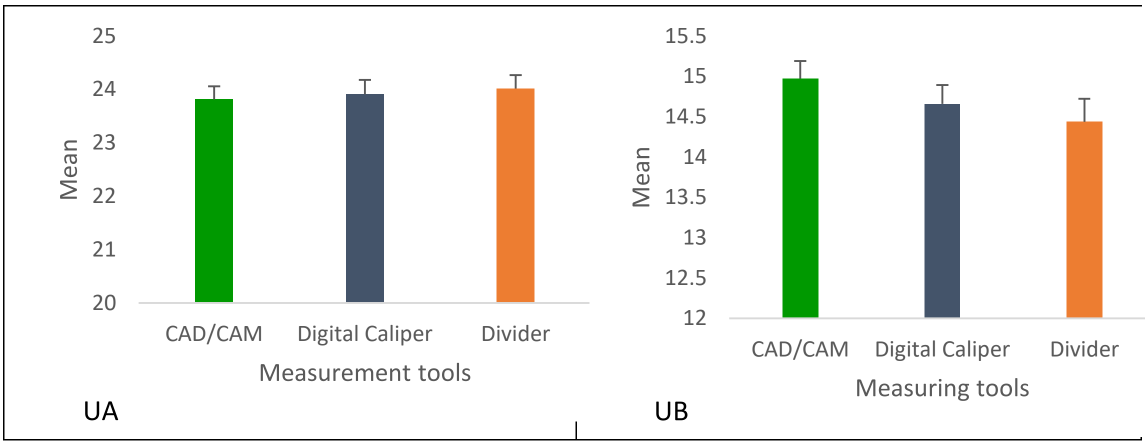
U = upper model

UA: segment from mesial of right first permanent molar to distal tip of right lateral incisor

UB: segment from distal tip of right lateral incisor to midline

UC: from midline to distal tip of the left lateral incisor.

UD: from distal tip of lateral incisor to mesial of left upper first permanent molar



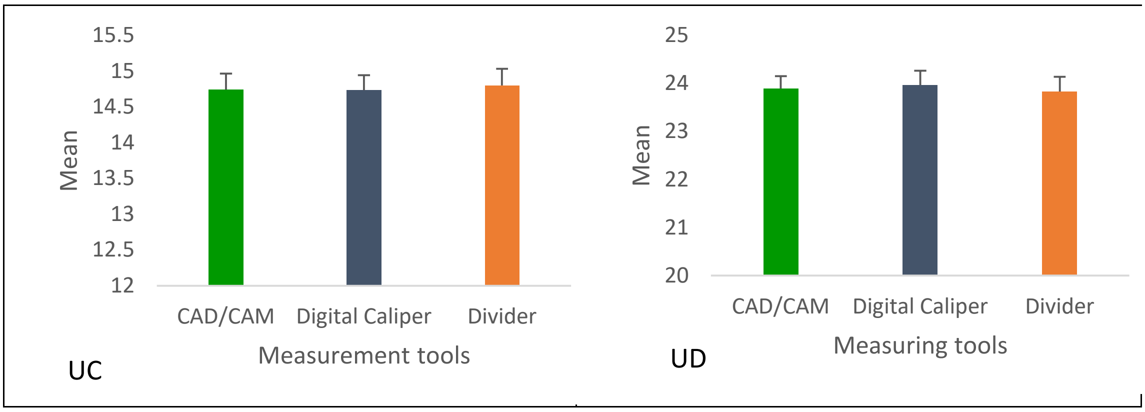


Figure 4.5 Mean values of four segments in upper models (UA-UD) for CAD/CAM, digital caliper and divider

B) Lower models

Table 4.11 Descriptive statistics and results of the statistical analysis of the arch perimeter measurements in millimetres (mm) for lower models performed using CAD/CAM, digital caliper and divider.

Segment	Measurement	Mean (±SD)	95% Confidence Interval for Mean		p-value
			Lower Interval	Upper Interval	
LA	CAD/CAM	21.89 (±0.34)	21.20	22.58	0.93
	Digital caliper	21.74(±0.37)	20.99	22.49	
	Divider	21.70 (±0.44)	20.79	22.61	
LB	CAD/CAM	10.89 (±0.12)	10.63	11.15	0.62
	Digital caliper	10.84 (±0.16)	10.51	11.18	
	Divider	11.03(±0.14)	10.75	11.32	
LC	CAD/CAM	10.78 (± 0.14)	10.49	11.07	0.68
	Digital caliper	10.56 (±0.20)	10.15	10.98	
	Divider	10.62 (±0.20)	10.20	11.03	
LD	CAD/CAM	21.63 (±0.32)	20.98	22.28	0.63
	Digital caliper	21.76 (±0.33)	21.09	22.42	
	Divider	22.05 (±0.32)	21.39	22.71	

SD= standard deviation

L=lower model

LA: mesial point of right lower first permanent molar to distal tip of right lateral incisor

LB: from the distal tip of right lateral incisor to midline

LC: from midline to distal tip of left lateral incisor

LD: from distal tip of left lateral incisor to mesial point of left first permanent molar

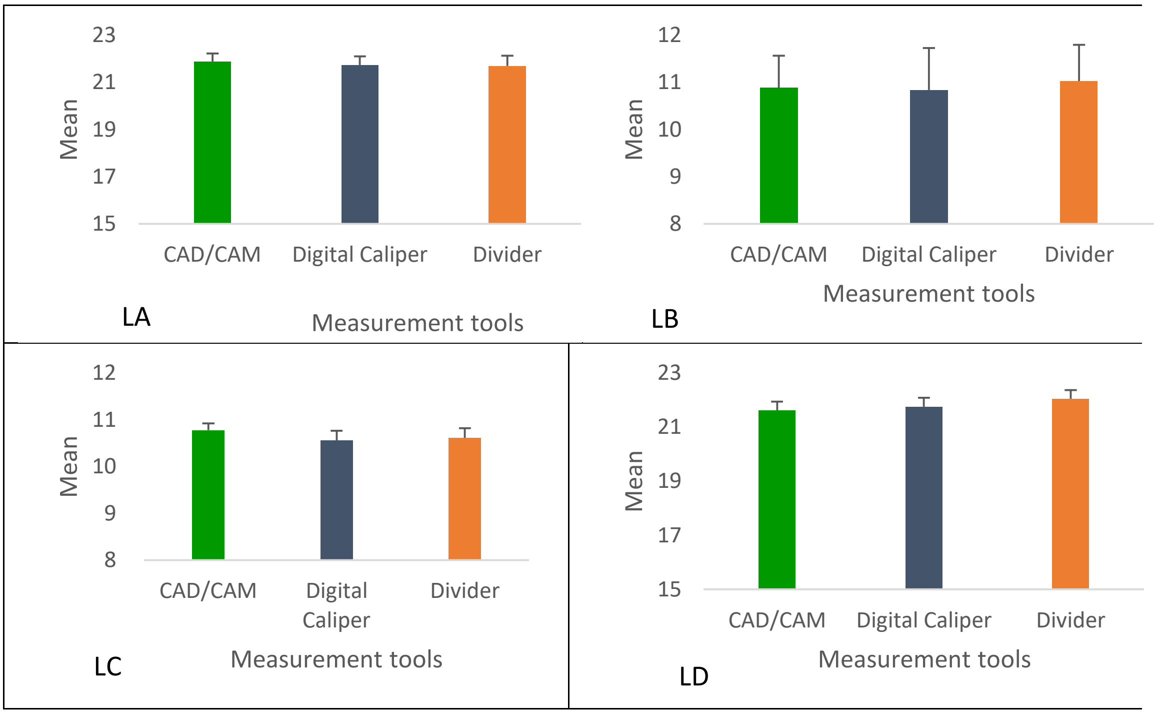


Figure 4.6 Mean values of four segments in lower models (LA-LD) for CAD/CAM, digital caliper and divider

4.3.2 Comparison of the total arch perimeter:

Table 4.12 Comparison of mean values and standard error between CAD/CAM, digital caliper and divider in upper and lower models.

Model	Measurement	Mean (±SE)
Upper	CAD/CAM	19.36 (± 0.43)
	Digital caliper	19.32 (± 0.44)
	Divider	19.27 (± 0.45)
Lower	CAD/CAM	16.30 (± 0.52)
	Digital caliper	16.22 (± 0.52)
	Divider	16.35 (± 0.53)

SE = standard error

Table 4.13 Mean difference, standard error and significant difference between upper and lower models using CAD/CAM, digital caliper and divider

			Mean Difference (±SE)	**p-value**
Model	**Measurement**			
Upper	**CAD/CAM**	**Digital caliper**	0.04 (±0.62)	1
		Divider	0.09 (± 0.62)	1
	Digital caliper	**CAD/CAM**	-0.04 (±0.62)	1
		Divider	0.05 (±0.62)	1
	Divider	**CAD/CAM**	-0.08 (± 0.62)	1
		Digital caliper	-0.05 (±0.62)	1
Lower	**CAD/CAM**	**Digital caliper**	0.07 (±0.74)	1
		Divider	-0.05 (± 0.74)	1
	Digital caliper	**CAD/CAM**	-0.07 (±0.74)	1
		Divider	-0.13 (±0.74)	1
	Divider	**CAD/CAM**	0.05 (±0.74)	1
		Digital Caliper	0.13 (±0.74)	1

SE=standard error

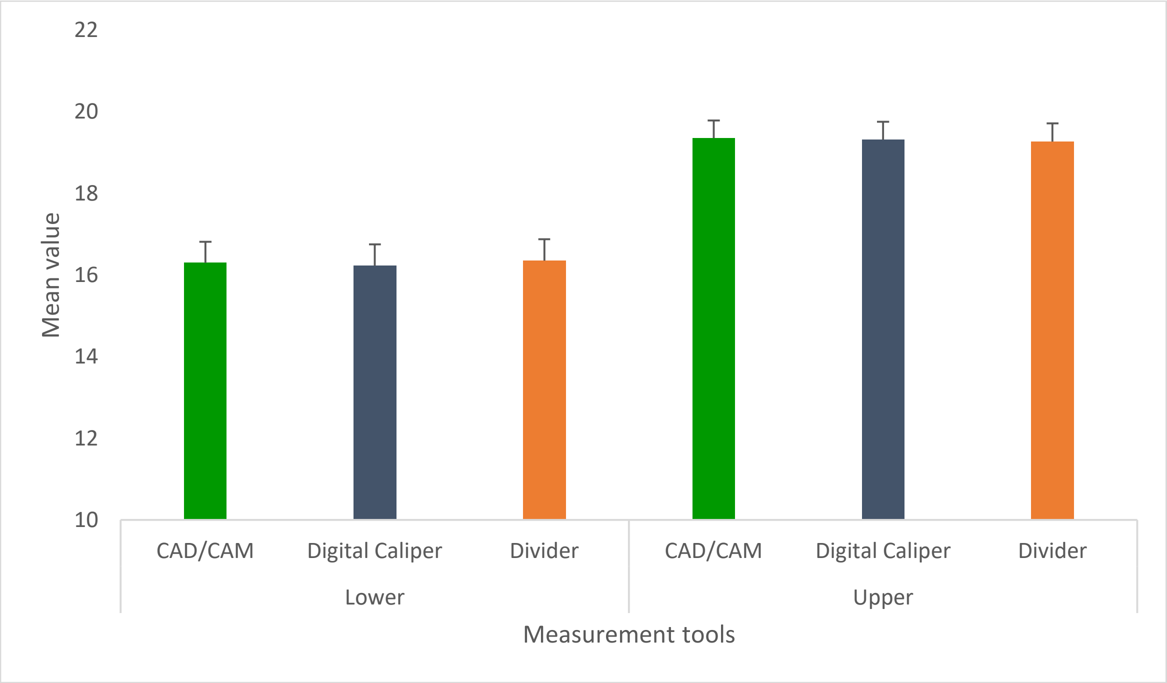


Figure 4.7 Comparison in mean values of total arch perimeter in upper and lower models between CAD/CAM, digital caliper and divider

4.4 Correction coefficient of the buccal segment

Manual calculations in percentage (%) were done by calculating the sum of premolars in each quadrant as follows:

Table 4.14 Mean values of the sum of premolar region in the four quadrants

Quadrant	**Mean values**		
	CAD/CAM	**Digital caliper**	**Divider**
Q1	13.7	13.76	14
Q2	13.74	13.76	14.11
Q3	14.12	14.33	14.57
Q4	13.97	14.5	14.68

Q1: Upper right quadrant (tooth number 15, 14)

Q2: Upper left quadrant (tooth number 25, 24)

Q3: Lower left quadrant (tooth number 35, 34)

Q4: Lower right quadrant (tooth number 45, 44)

The CAD/CAM value will represent a percentage of 100 (as gold standard). The correction coefficient needed for the digital caliper and divider to have the accurate measurement as CAD/CAM is provided in the tables below.

Table 4.15 Correction coefficient of buccal segment quadrant 1

Digital caliper	-0.44 %
Divider	-2.19 %

Table 4.16 Correction coefficient of buccal segment quadrant 2

Digital caliper	-0.145 %
Divider	-2.73 %

Table 4.17 Correction coefficient of buccal segment quadrant 3

Digital caliper	-1.487 %
Divider	-3.186 %

Table 4.18 Correction coefficient of buccal segment quadrant 4

Digital caliper	-3.79 %
Divider	-5.05 %

CHAPTER 5: DISCUSSION

5.1 Operator reliability

5.1.1 Tooth widths measurements

The operator calibration indicated that tooth widths measurements for Sirona inEos Blue (CAD/CAM) was highly correlated ($p > 0.05$) as analyzed using the Pearson correlation coefficient in the paired t-test shown in Table 4.1.

The examiner reliability in three dimensional measurements was also high in a study by Nouri *et al* (2014) (Nouri *et al.*, 2014). The difference between the initial measurements and repeated measurements was insignificant; a minor limitation was locating the same exact point twice on the teeth in the digital model, because of the high definition that could be viewed on the 3D rendering of the CAD/CAM software of the plaster model scan. During the pilot study a lead pencil was used to make dots on the mesial and distal surfaces to attempt to enhance the consistency. After the CAD/CAM scan was completed, it was realised that the scan detail far surpass the position of where the naked eye chose the position for the dot. It was subsequently decided that a greater accuracy is possible by applying the CAD/CAM measuring tool directly on the 3D rendering. Also, this will be clinically relevant to not use a pencil on the teeth, since the direct intra-oral scan with the Sirona intra-oral camera is the appropriate technique the clinician will use for the CAD/CAM space analysis technique.

In Sirona inEos Blue software (CAD/CAM) a 'click and drag' method was used when the pinpoint was located in the mesial and distal points. The same method was used in OrthoCAD in a study by Tomassetti *et al* (2001) (Tomassetti *et al.*, 2001). Also, the advantage given with CAD/CAM is that the digital model can be rotated and zoomed in order to accurately locate the points that are difficult to be reached when using digital caliper or divider. Hence, the use of digital models offers good visualization that is not possibly done with plaster models (Zilberman *et al.*, 2003). Fleming *et al* (2011) and Houston (1983) concluded in their study that there is difficulty in being precise about a particular point or landmark when using digital model or computerized models (Houston, 1983; Fleming *et al.*, 2011). Therefore, it is a source of random errors.

When using the digital caliper, there was no statistically significant difference ($p > 0.05$) between the measurements as shown in Table 4.2. However, tooth widths measurements done using the divider showed a significant difference in the measurements done in both times ($p < 0.05$) as shown in Table 4.3. This is due to the error during transfer of the divider reading to a ruler.

5.1.2 Arch perimeter measurements

Table 4.4 shows the arch perimeter measurements done using Sirona inEos Blue (CAD/CAM). The p-value was more than 0.05, thus the difference between the initial and repeated measurements was not statistically significant. Whereas, measurements done using digital caliper and divider showed some difference Table 4.5 and 4.6.

A degree of error is sometimes inevitable due to several reasons. First, these measurements were done by one operator. Second, there is always an error that is associated with the measurement of physical objects which is explained by the statistical variability within all three methods (Akyalcin *et al.*, 2013). In most studies that compared manual and digital models, results showed that more experienced operators had fewer errors than did the operators with less experience with both tools (Othman and Harradine, 2007 ; Wan Hassan *et al.*,2016).

Divider is an easy method of measurement that is adopted in dental schools and is a convenient method of learning for beginners (da Costa *et al.*, 2016). It was also found to be accurate compared to brass wire. However, da Costa *et al* (2016) concluded that the use of the divider was to minimize the errors. While in this study there were some errors in measuring tooth widths and arch perimeter, when transferring the reading to the ruler.

5.2 Comparison of tooth widths measurements between Sirona inEos Blue (CAD/CAM), digital caliper and divider

In this study, the comparison was in linear measurements used for space analysis (mesio-distal tooth widths and arch perimeter measured in four segments) between all measuring devices. From a statistical point of view the agreement between the three methods was necessary in order to reach a conclusion on the most accurate method.

From Table 4.7 the overall mean ± SE (standard error) of CAD/CAM was less than that of digital caliper and divider. Accordingly, CAD/CAM measurements were the most accurate above all. Santoro *et al* (2003) also shared the same agreement where measurements of the digital models were smaller than direct measurements of plaster models with calipers (Santoro *et al.*, 2003). On the contrary, Tran *et al* (2003) and Quimby *et al* (2004) demonstrated that measurements using digital models were slightly larger than direct measurements in plaster models. However, they concluded that the difference was statistically insignificant (Tran *et al.,* 2003; Quimby *et al*., 2004).

When comparing between all methods of measurement, Table 4.8 shows a significant difference between the CAD/CAM and the divider ($p < 0.05$). Also, a significant difference exists when comparing the measurements by digital caliper and divider measurements ($p < 0.05$). However, there was no significant difference when comparing CAD/CAM to digital caliper. Standard error was the same for all measurement tools (0.06).The divider had the highest upper interval compared to CAD/CAM and digital caliper as shown in Figure 4.1. A significant difference was found in studies by Mullen *et al* (2007) and Goonewardene *et al* (2008) when the mesio-distal widths were measured. However, the errors were accounted as clinically acceptable (Mullen *et al.*, 2007; Goonwardene *et al.*, *2008*). Large measurements can be explained by an overestimation in the mesio-distal tooth widths measured by the digital caliper and the divider compared to CAD/CAM. The current study findings corroborates with other studies that found no statistical significant difference between digital and plaster models (Bell *et al.*, 2003; Horton *et al.*, 2010). However, in studies that found some statistical differences, it was not clinically significant (Stevens *et al.*, 2006; Mullen *et al.* 2007; Nouri *et al.*, 2014). Rheude *et al* (2005) reached the same finding in diagnosis and treatment planning (Rheude *et al.*, 2005). Also, in a systematic review by Fleming *et al* (2011) reported that the difference between the mean of plaster models and digital models was low and was accounted in all studies revised as clinically insignificant (Fleming *et al.*, 2011). The available evidence was of variable quality however, the review concluded a high degree of validity when comparing digital models to plaster models and the use of digital models was clinically acceptable (Fleming *et al.*, 2011).

5.2.1 Correlation between CAD/CAM, digital caliper and divider

The Pearson correlation was used to estimate the strength of the linear relationship between each measuring tool as follows:

1) CAD/CAM and digital caliper
2) CAD/CAM and divider
3) Digital caliper and divider

Although the digital caliper and the divider displayed good correlation with CAD/CAM, the digital caliper had the highest correlation with the CAD/CAM. Table

4.9; Figure 4.2 shows the strong linear correlation of a positive value 0.95 (closer to 1). The difference was not significant between the aforementioned measurement tools ($p > 0.05$). Following that was the correlation between the digital caliper and the divider with a positive value of 0.93 and 0.91 between the CAD/CAM and the divider. The correlation was highly significant between CAD/CAM and the divider ($p < 0.05$). Also, a statistically significant difference existed looking at the p-value less than 0.05 between the digital caliper and the divider.

Furthermore, Stevens *et al* (2006) and Redlich *et al* (2008) reported no statistical difference between conventional and digital methods despite the good correlation found between the measurements (Stevens *et al.,* 2006; Redlich *et al.,* 2008).

5.3 Arch perimeter comparison

5.3.1 Individual

The four segments of arch perimeter in both upper and lower models were compared individually as shown in Table 4.10 and 4.11. The results showed there was no statistical significant difference between CAD/CAM, digital caliper and divider ($p > 0.05$).

Arch length can be measured in different ways; either using brass wire or measured in four or six segments. It is measured from mesial of one molar to mesial of contralateral molar (Tanaka and Johnston, 1974). Goonewardene *et al* (2008) have assessed the arch length in two different segment divisions; four and six. However, there were some limitations in these measurements where the points in the canine region may be difficult to identify thus this may end up with an inaccurate estimation of the arch form (Goonewardene *et al.,* 2008). In that study although the measurements of digital models were larger in mean arch length measurements, the difference was not significant: upper models (plaster vs digital) with p-value of 0.73, lower models (plaster vs digital) p-value 0.13. Measurements were accurate from both plaster and digital models, both measurements with OrthoCAD and digital caliper had excellent repeatability (Goonewardene *et al.*, 2008).

5.3.2 Total arch perimeter

Mean difference (± SD) of CAD/CAM in the upper models was more 19.36 (± 0.43) mm compared to digital caliper and the divider. The findings agree with some studies such as Goonewardene *et al* (2008) and Tran *et al* (2003) (Tran *et al.*, 2003; Goonewardene *et al.*, 2008). In the previous studies the difference might be as a result of the distortion that had occurred to the impression material (Goonewardene *et al.*, 2008). However, in the lower models, the divider had larger measurement of 16.35 (± 0.53) mm than CAD/CAM and the digital caliper, as shown in Table 4.12. When the arch perimeter was compared between the three measurement methods i.e. CAD/CAM, digital caliper and divider, there was no statistical significant difference (p = 1). This explains the negative values of the mean difference seen in Table 4.13. The results in arch perimeter analysis agree with the results by Goonewardene *et al* (2008). There was no statistical difference between manual and computer measurements (Goonewardene *et al.*, 2008).

5.4 Correction coefficient of the buccal segment

Crowding in the premolar region is influenced by several factors. For example, one of the factors is the early loss of deciduous teeth followed by the mesial movement of first permanent molars (Shigembu *et al.*, 2007). Due to the design of the digital caliper and the divider it might not be possible to accurately access the premolar region for tooth widths measurements.

In this study, there was an attempt to calculate a correction coefficient of the premolar region in percentage for the digital caliper and the divider. The CAD/CAM measurements set the gold standard in this study (100% accuracy). Thus, the premolar region was measured and summed in all four quadrants. The calculations were done where the CAD/CAM mean value presented 100% as shown in Table 4.14. Due to the crowding that might occur in that specific region, the CAD/CAM is able to locate a specific point or landmark. Using the digital model, it is possible to rotate, zoom in and out, in order to accurately locate a point with the cursor.

Tables (4.15-4.18) show the correction coefficient of the premolar region for the digital caliper and the divider in all four quadrants. Digital caliper with normal thick points (Figure 3.8) allows for interproximal space access especially in the buccal premolar segment measurement. On the other hand, the divider is a widely used measuring method that is accurate according to da Costa *et al* (2016) (da Costa *et al.*, 2016). However, the limitation of the divider is the 'rounding up' of the values which can be inconsistent. This will result in either overestimate or underestimate the space available and/or tooth size present on the model when the manual measurement is transferred to the ruler. This was also seen with the measurement of buccal premolar segment. The effect of rounding of values was seen in all four quadrants.

The percentage ranged between 0.145% to 3.79% for the digital caliper and 2.19% to 5.05% for the divider. Therefore, this is the percentage needed in order to get the accurate measurement of the CAD/CAM.

CHAPTER 6: CONCLUSION

This study was aimed at adding value to the use of digital models for space analysis using CAD/CAM. It has become available in private practices. The measurements recorded for space analysis with the CAD/CAM in comparison to the traditional methods of measurements such as digital caliper and divider sowed a standard deviation of all three methods up to 0.01 mm from one another. This small difference between the techniques illustrates how close the investigator was equally accurate for tooth size and arch perimeter analysis. Moreover, based on the p-values and Pearson's correlation both tooth widths and arch perimeter measurements illustrated no significant differences. The null hypothesis that there was no difference between the techniques in measurements done on plaster models and digital models in this study was well supported by the findings in the literature. According to previous studies the difference illustrated in this study between various techniques is accounted in the literature as clinically insignificant with an average of less than 0.5 mm difference between the measurements of the plaster and the digital version of the models (Bell *et al.,* 2003; Santoro *et al.,* 2003; Leifert *et al.,* 2009; Hassan *et al.,* 2016; Rossini *et al.,* 2016).

It can be concluded from this study that old/archived plaster models stored as records can be converted to digital models as it will have the same accuracy of measurements. Additionally, space analysis can be performed with similar reliability on the digital models. Therefore, digital models have the advantage to replace plaster models in the field of orthodontics for record keeping, treatment planning and monitoring the treatment progress.

With regard to the buccal segment, challenges existed with the space analysis for the premolar region. The buccal correction coefficient, although being a small percentage of correction, it could be significant if the operator is not experienced with the divider or the caliper has thick ends that do not fit well between the teeth. In those border line premolar extraction cases that 1% of space might change the treatment plan.

6.1 Limitations of the study

The buccal correction coefficient could have been tested for its validity, but within the scope of this thesis, the correction coefficient indicated its accuracy for the conversion of plaster models to digital models at the very least.

The CAD/CAM system used was a crown and bridge platform and not one of the established orthodontic platforms. The authors had the rationale of many laboratories and dental practices that have crown and bridge platforms. This could have a wide reaching affect for the majority of general practitioners that want to use their CAD/CAM platform for a space analysis prior referral to specialists or simply enhance the holistic treatment approach that many modern general practices offer. CAD/CAM software from Sirona Dentsply does not offer a "short cut" to the measuring tool after the model or if an intra-oral scan were to be made. It would be advisable for an application to be added by Sirona Dentsply for the space analysis of the teeth and arch perimeter.

6.2 Recommendations

The buccal correction coefficient can be tested as a retrospective study on orthodontic cases where there are a case series of models available. This evaluation of the initial space analysis compared to the space analysis with the application of the "buccal correction coefficient" will indicate if the treatment plan would have taken an alternate route. It is advisable to assess the cases where premolars needed to be extracted as these cases could very well benefit the most from the buccal correction coefficient.

CAD/CAM has shown its accuracy for intra-oral and extra-oral plaster models scans, the application of the measuring tool for space analysis in the existing CAD/CAM platform from Sirona Dentsply can be clinically acceptable and ideal for practitioners that want to apply space analysis as part of their practices' digital platforms.

Further studies can be completed to evaluate the use of a series of digital models for tracking and evaluating the differences in the treatment progression. Despite the accuracy, reliability and reproducibility of digital model analysis in the CAD/CAM platform, a time and space saving feature could be a plausible solution to a common problem in orthodontics.

REFERENCES

Akyalcin, S., Dyer, D.J., English, J.D. and Sar, C., 2013. Comparison of 3-dimensional dental models from different sources: Diagnostic accuracy and surface registration analysis. *American Journal of Orthodontics and Dentofacial* Orthopedics, 144(6), pp.831-837.

Bell, A., Ayoub, A.F. and Siebert, P., 2003. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. *Journal of orthodontics*, 30(3), pp.219-23.

Beuer, F., Schweiger, J. and Edelhoff, D., 2008. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *British dental journal*, *204*(9), p.505-511.

Bindl, A. and Mörmann, W.H., 2005. Marginal and internal fit of all-ceramic CAD/CAM crown-copings on chamfer preparations. *Journal of oral rehabilitation*, *32*(6), pp.441-447.

Black, G.V., 1902. Descriptive anatomy of the human teeth. SS White manufacturing Company.

Bohner, L.O.L., Canto, G.D.L., Marció, B.S., Laganá, D.C., Sesma, N. and Neto, P.T., 2017. Computer-aided analysis of digital dental impressions obtained from intraoral and extraoral scanners. *Journal of Prosthetic Dentistry*, *118*(5), pp.617-623.

Bolton, W.A., 1958. Disharmony in tooth size and its relation to the analysis and treatment of malocclusion. *The Angle Orthodontist*, *28*(3), pp.113-130.

Budak, I., Vukelić, D., Bračun, D., Hodolič, J. and Soković, M., 2012. Pre-processing of point-data from contact and optical 3D digitization sensors. *Sensors*, *12*(1), pp.1100-1126.

Champagne, M., 1992. Reliability of measurements from photocopies of study models. *Journal of clinical orthodontics: JCO*, *26*(10), p.648-650.

Creed, B., Kau, C.H., English, J.D., Xia, J.J. and Lee, R.P., 2011, March. A comparison of the accuracy of linear measurements obtained from cone beam computerized tomography images and digital models. *Seminars in orthodontics* (Vol. 17, No. 1, pp. 49-56). Elsevier.

Da Costa, C.T., Flores, I.L., Al-Alam, F., e Silva, M.S., Martins, P., Goulart, T., Tremea, D. and Bonow, M.L.M., The bow divider is an appropriate method to space measurement in mixed dentition by undergraduate students. *Centro*, *35010*, p.173-177.

Davidowitz, G. and Kotick, P.G., 2011. The use of CAD/CAM in dentistry. *Dental Clinics of North America*, 55(3), pp.559-570.

Duret, F., Blouin, J.L. and Duret, B., 1988. CAD-CAM in dentistry. *The Journal of the American Dental Association*, 117(6), pp.715-720.

El-Zanaty, H.M., El-Beialy, A.R., El-Ezz, A.M.A., Attia, K.H., El-Bialy, A.R. and Mostafa, Y.A., 2010. Three-dimensional dental measurements: an alternative to plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics*, *137*(2), pp.259-265.

Fleming, P.S., Marinho, V. and Johal, A., 2011. Orthodontic measurements on digital study models compared with plaster models: a systematic review. *Orthodontics & craniofacial research*, *14*(1), pp.1-16.

Goonewardene, R.W., Goonewardene, M.S., Razza, J.M. and Murray, K., 2008. Accuracy and validity of space analysis and irregularity index measurements using digital models. *Australian orthodontic journal*, *24*(2), p.83-90.

Hamza, T.A., Ezzat, H.A., El-Hossary, M.M.K., Katamish, H.A.E.M., Shokry, T.E. and Rosenstiel, S.F., 2013. Accuracy of ceramic restorations made with two CAD/CAM systems. *Journal of Prosthetic Dentistry*, *109*(2), pp.83-87.

Hassan, W.N.W., Othman, S.A., Chan, C.S., Ahmad, R., Ali, S.N.A. and Rohim, A.A., 2016. Assessing agreement in measurements of orthodontic study models: Digital caliper on plaster models vs 3-dimensional software on models scanned by structured-light scanner. *American Journal of Orthodontics and Dentofacial Orthopedics*, *150*(5), pp.886-895.

Horton, H.M., Miller, J.R., Gaillard, P.R. and Larson, B.E., 2010. Technique comparison for efficient orthodontic tooth measurements using digital models. *The Angle Orthodontist*, *80*(2), pp.254-261.

Houston WJB, 1983. The analysis of errors in orthodontic measurements. *American Journal of Orthodontics*, 83(5), pp. 382–390.

Howes, A.E., 1947. Case analysis and treatment planning based upon the relationship of the tooth material to its supporting bone. *American Journal of Orthodontics and Oral Surgery*, 33(8), pp.499-533.

Jacob, H.B., Wyatt, G.D. and Buschang, P.H., 2015. Reliability and validity of intraoral and extraoral scanners. *Progress in orthodontics*, 16(1), pp.1-6.

Joffe, L., 2004. Current Products and Practices OrthoCAD™: digital models for a digital era. *Journal of Orthodontics*, *31*(4), pp.344-347.

Kau, C.H., Littlefield, J., Rainy, N., Nguyen, J.T. and Creed, B., 2010. Evaluation of CBCT digital models and traditional models using the Little's Index. *Angle Orthodontist*, *80*(3), pp.435-439.

Kirsch, C., Ender, A., Attin, T. and Mehl, A., 2017. Trueness of four different milling procedures used in dental CAD/CAM systems. *Clinical oral investigations*, *21*(2), pp.551-558.

Leifert, M.F., Leifert, M.M., Efstratiadis, S.S. and Cangialosi, T.J., 2009. Comparison of space analysis evaluations with digital models and plaster dental casts. *American Journal of Orthodontics and Dentofacial Orthopedics*, 136(1), pp.16-e1.

Luthardt, R.G., Loos, R. and Quaas, S., 2005. Accuracy of intraoral data acquisition in comparison to the conventional impression. *International journal of computerized dentistry*, *8*(4), pp.283-294.

Mayers, M., Firestone, A.R., Rashid, R. and Vig, K.W., 2005. Comparison of peer assessment rating (PAR) index scores of plaster and computer-based digital models. *American journal of orthodontics and dentofacial orthopedics*, *128*(4), pp.431-434.

Melkos, A.B., 2005. Advances in digital technology and orthodontics: a reference to the Invisalign method. *Medical science monitor*, 11(5), pp.PI39-PI42.

Mok, K.H. and Cooke, M.S., 1998. Space analysis: a comparison between sonic digitization (DigiGraph™ Workstation) and the digital caliper. *European journal of orthodontics*, *20*(6), pp.653-661.

Moldovan, O., Luthardt, R.G., Corcodel, N. and Rudolph, H., 2011. Three-dimensional fit of CAD/CAM-made zirconia copings. *Dental Materials*, *27*(12), pp.1273-1278.

Moreira, D.D., Gribel, B.F., Torres, G.D.R., Vasconcelos, K.D.F., Freitas, D.Q.D. and Ambrosano, G.M.B., 2014. Reliability of measurements on virtual models obtained from scanning of impressions and conventional plaster models. *Brazilian Journal of Oral Sciences*, *13*(4), pp.297-302.

Mullen, S.R., Martin, C.A., Ngan, P. and Gladwin, M., 2007. Accuracy of space analysis with emodels and plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics*, 132(3), pp.346-352.

Neff, C.W., 1949. Tailored occlusion with the anterior coefficient. *American journal of orthodontics, 35(4), pp.309-313.*

Ng, J., Ruse, D. and Wyatt, C., 2014. A comparison of the marginal fit of crowns fabricated with digital and conventional methods. *Journal of Prosthetic Dentistry*, *112*(3), pp.555-560.

Nouri, M., Asefi, S., Baghban, A.A., Aminian, A., Shamsa, M. and Massudi, R., 2014. Validity and reliability of a three-dimensional dental cast simulator for arch dimension measurements. *Dental research journal*, *11*(6), p.656-662.

Okunami, T.R., Kusnoto, B., BeGole, E., Evans, C.A., Sadowsky, C. and Fadavi, S., 2007. Assessing the American Board of Orthodontics objective grading system: digital vs plaster dental casts. *American Journal of Orthodontics and Dentofacial Orthopedics*, 131(1), pp.51-56.

Periago DR, Scarfe WC, Moshiri M, Scheetz JP, Silveira AM, Farman AG., 2008.. Linear accuracy and reliability of cone beam CT derived 3-dimensional images constructed using an orthodontic volumetric rendering program. *The Angle Orthodontist*, 78(3), pp.387–395.

Quimby, M.L., Vig, K.W., Rashid, R.G. and Firestone, A.R., 2004. The accuracy and reliability of measurements made on computer-based digital models. *The Angle orthodontist*, 74(3), pp.298-303.

Redlich, M., Weinstock, T., Abed, Y., Schneor, R., Holdstein, Y. and Fischer, A., 2008. A new system for scanning, measuring and analyzing dental casts based on a 3D holographic sensor. *Orthodontics & craniofacial research*, 11(2), pp.90-95.

Redmond, W.R., 2001. Digital models: a new diagnostic tool. *Journal of clinical orthodontics*, 35(6), pp.386-387.

Reich, S., Wichmann, M., Nkenke, E. and Proeschel, P., 2005. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. *European journal of oral sciences*, *113*(2), pp.174-179.

Rheude, B., Lionel Sadowsky, P., Ferriera, A. and Jacobson, A., 2005. An evaluation of the use of digital study models in orthodontic diagnosis and treatment planning. *The Angle Orthodontist*, *75*(3), pp.300-304.

Rossini, G., Parrini, S., Castroflorio, T., Deregibus, A. and Debernardi, C.L., 2016. Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: A systematic review. *American journal of orthodontics and dentofacial orthopedics*, *149*(2), pp.161-170.

Santoro, M., Galkin, S., Teredesai, M., Nicolay, O.F. and Cangialosi, T.J., 2003. Comparison of measurements made on digital and plaster models. *American journal of orthodontics and dentofacial orthopedics*, 124(1), pp.101-105.

Shigenobu, N., Hisano, M., Shima, S., Matsubara, N. and Soma, K., 2007. Patterns of dental crowding in the lower arch and contributing factors: a statistical study. *The Angle Orthodontist*, *77*(2), pp.303-310.

Stevens, D.R., Flores-Mir, C., Nebbe, B., Raboud, D.W., Heo, G. and Major, P.W., 2006. Validity, reliability, and reproducibility of plaster vs digital study models: comparison of peer assessment rating and Bolton analysis and their constituent measurements. *American journal of orthodontics and dentofacial orthopedics*, *129*(6), pp.794-803.

Tanaka, M.M. and Johnston, L.E., 1974. The prediction of the size of unerupted canines and premolars in a contemporary orthodontic population. *The Journal of the American Dental Association*, *88*(4), pp.798-801.

Tapie, L., Lebon, N., Mawussi, B., Fron, H.C., Duret, F. and Attal, J.P., 2015. Understanding dental CAD/CAM for restorations--the digital workflow from a mechanical engineering viewpoint. *International journal of computerized dentistry*, *18*(1), pp.21-44.

Tarazona, B., Llamas, J.M., Cibrian, R., Gandia, J.L. and Paredes, V., 2011. A comparison between dental measurements taken from CBCT models and those taken from a digital method. *The European Journal of Orthodontics*, *35*(1), pp.1-6.

Tinschert, J., Natt, G., Mautsch, W., Spiekermann, H. and Anusavice, K.J., 2001. Marginal fit of alumina-and zirconia-based fixed partial dentures produced by a CAD/CAM system. *Operative dentistry*, *26*(4), pp.367-374.

Tinschert, J., Zwez, D., Marx, R. and Anusavice, K.J., 2000. Structural reliability of alumina-, feldspar-, leucite-, mica-and zirconia-based ceramics. *Journal of dentistry*, *28*(7), pp.529-535.

Tomassetti, J.J., Taloumis, L.J., Denny, J.M. and Fischer Jr, J.R., 2001. A comparison of 3 computerized Bolton tooth-size analyses with a commonly used method. *The Angle Orthodontist*, *71*(5), pp.351-357.

Tran , A.M., Rugh, J.D., Chacon, J.A. and Hatch, J.P., 2003. Reliability and validity of a computer-based Little irregularity index. *American journal of orthodontics and dentofacial orthopedics*, *123*(3), pp.349-351.

Trifkovic, B., Budak, I., Todorovic, A., Vukelic, D., Lazic, V. and Puskar, T., 2014. Comparative analysis on measuring performances of dental intraoral and extraoral optical 3D digitization systems. *Measurement*, *47*, pp.45-53.

de Waard, O., Rangel, F.A., Fudalej, P.S., Bronkhorst, E.M., Kuijpers-Jagtman, A.M. and Breuning, K.H., 2014. Reproducibility and accuracy of linear measurements on dental models derived from cone-beam computed tomography compared with digital dental casts. *American journal of orthodontics and dentofacial orthopedics*, *146*(3), pp.328-336.

Wheeler RC, A textbook of dental anatomy and physiology. Philadelphia : W.B.Saunders 1961

Wiechmann, D., Rummel, V., Thalheim, A., Simon, J.S. and Wiechmann, L., 2003. Customized brackets and archwires for lingual orthodontic treatment. *American journal of orthodontics and dentofacial orthopedics*, 124(5), pp.593-599.

Wolf, P.D.M., Schumacher, P., Jäger, F., Wego, J., Fritz, U., Korbmacher-Steiner, H., Jäger, A. and Schauseil, M., 2015. Novel lingual retainer created using CAD/CAM technology. *Journal of Orofacial Orthopedics/Fortschritte der Kieferorthopädie*, *76*(2), pp.164-174.

Yee, S.H.X., Esguerra, R.J., Chew, A.A.Q.A., Wong, K.M. and Tan, K.B.C., 2018. Three-Dimensional Static Articulation Accuracy of Virtual Models–Part I: System Trueness and Precision. *Journal of Prosthodontics*, *27*(2), pp.129-136.

Zilberman, O., Huggare, J. and Parikakis, K.A., 2003. Evaluation of the validity of tooth size and arch width measurements using conventional and three-dimensional virtual orthodontic models. *The Angle orthodontist*, *73*(3), pp.301-306.

https://www.dentsply.com/en-us/prosthetics/cad-cam.html#tabs=MultiMat2Sinter

www.sirona.com