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Correlation of Tooth Length Measurements made on CBCT and 3T MR Images

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LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
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Correlation of Tooth Length Measurements made on CBCT and 3T MR Images

by

Andrew Scott Taylor

A Thesis submitted in partial satisfaction of
the requirements for the degree
Master of Science in Orthodontics and Dentofacial Orthopedics

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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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CONTENT

FIGURES

Figure Page

TABLES

Table Page

ABBREVIATIONS

3D	Three-dimensional
CBCT	Cone Beam Computed Tomography
MR	Magnetic Resonance
TMJ	Temporomandibular Joint
3T	3-Tesla
2D	Two-dimensional
CT	Multi-detector Computed Tomography
ALARA	As Low As Reasonably Achievable
ADA	American Dental Association
AAO	American Association of Orthodontists
AAOMR	American Academy of Oral and Maxillofacial Radiology
IRB	Institutional Review Board
LLUSD	Loma Linda University School of Dentistry
FOV	Field of View
DICOM	Digital Imaging and Communications in Medicine
MP-RAGE	Magnetization Prepared Rapid Acquisition by Gradient Echo
ANS	Anterior Nasal Spine
PNS	Posterior Nasal Spine
ICC	Intraclass Correlation Coefficient
LLUMC	Loma Linda University Medical Center

ABSTRACT OF THE THESIS

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Master of Science, Graduate Program in Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2016
Dr. V. Leroy Leggitt, Chairperson

Objective. This study compared tooth length measurements made on cone beam computed tomography (CBCT) scans and 3-Tesla (3T) magnetic resonance (MR) scans performed with and without an alginate bite registration surrounding the crowns of the teeth.

Materials and Methods. One CBCT scan, one MR scan with alginate bite registration, and one MR scan without bite registration were performed on 12 subjects. The alginate bite registration was used to provide a proton-rich material to surround proton-poor teeth in an attempt to improve visualization of teeth. DICOM formatted images from each of the three scans for each subject were oriented in all three planes of space. Slices of 4 mm thickness were made through all permanent teeth. Tooth length measurements were made from the slices.

Results. The presence of alginate bite registration during MR scans made it impossible to determine tooth lengths on MR images. Tooth lengths measured from CBCT and MR scans without alginate bite registration were very highly correlated. For 336 measurements (N = 336) the correlation coefficient was found to be 0.953 ($p < 0.001$).

Conclusions. 1.) Alginate is not a useful material in increasing visualization of teeth on MR scans. 2.) Tooth length measurements made on MR scans are highly correlated with tooth length measurements made on CBCT scans.

CHAPTER ONE

INTRODUCTION

Statement of Purpose

In orthodontic practice it is often necessary to take several radiographic images for the purposes of diagnosis and treatment planning. Historically these images have included lateral cephalograms, panoramic radiographs, and full mouth surveys including multiple periapical and bitewing images. Over the past two decades, these images have been increasingly supplemented by three-dimensional (3D) imaging technologies, in particular cone beam computed tomography (CBCT). In addition to initial diagnostic images, it is also often necessary for orthodontists to take supplementary cephalograms, panoramic x-rays, and periapical images during the course of treatment to evaluate treatment progress. Many orthodontists also take radiographic final records at the end of treatment to evaluate final tooth positions. Although these images are useful for diagnosis and treatment planning and have the additional benefit of identifying existing hard tissue pathology in the head and neck, there is concern about exposing orthodontic patients to increased levels of ionizing radiation.

Magnetic resonance (MR) imaging is a technology that yields 3D imaging of the head and neck area and does not expose patients to ionizing radiation. MR images provide visualization of both hard and soft tissue structures including the temporomandibular joint (TMJ), articular disk, and the pharyngeal airway. These structures are of interest to orthodontists, but are often not visible or not measurable using conventional imaging technologies. However, despite the advantages of MR imaging in terms of patient safety and visualization of particular head and neck features, this technique has not been evaluated as an alternative to current forms of orthodontic imaging.

The purpose of this study was to determine if 3-Tesla (3T) MR scans are accurate in determining tooth lengths compared to CBCT scans. If so, orthodontic diagnosis may be performed using MR images, decreasing ionizing radiation exposure for patients. In addition, this study evaluated tooth length measurements from MR scans of crowns coated in contrast media and not coated in contrast media to determine whether the use of contrast media improved visualization of crown morphology and accuracy of tooth length measurements using MR scanning. The contrast media used for this study was alginate impression material.

Review of Literature

Traditional orthodontic imaging relies on the evaluation of two-dimensional (2D) images to approximate 3D structures. However it is impossible to ascertain depth or determine exact positions of structures in the head and neck with 2D imaging.[1] Because comprehensive visualization of craniofacial structures is important in orthodontics, 3D imaging technologies are becoming increasingly popular.[2] Specific applications for 3D imaging in the field of orthodontics include identifying impacted tooth positions, evaluating root resorption, assessing fractured roots, placing orthodontic implants, evaluating facial asymmetries, measuring size and shape of osseous defects, assessing the TMJ, analyzing the airway, identifying pathologies, and simulating orthognathic surgery.[3] In addition, 3D imaging provides information regarding root length, position, angulation, and inclination which can be of value to the orthodontist when developing treatment plans.[4]

The most popular form of 3D imaging technology used in orthodontics today is CBCT.[3] Because of its popularity, the number of research studies involving CBCT has increased dramatically in recent years.[4] These studies help to elicit the advantages of CBCT including lower cost, accurate data, lower radiation than multi-detector computed tomography (CT), quicker scans, and easier visualization and image processing using a personal computer.[5,6,7,8] However, CBCT has some disadvantages as well. One of these is that it exposes patients to risks from ionizing radiation. The amount of radiation generated by a CBCT scan is dependent upon the manufacturer and CBCT unit settings.[9]

While many individual studies suggest that radiation exposure to patients during CBCT scans is relatively low, a systematic review by De Vos et al., suggests that there are inconsistencies in reporting of the data. This systematic review of CBCT studies concludes that the statistics reported for radiation exposure do not appear to be scientifically based: "The increasing popularity of CBCT has resulted in numerous presentations at conferences, dozens of manufacturers' brochures and published papers resulting in an uncontrolled and non-evidence-based exchange of radiation dose values. In conclusion, the results of this review showed that there is a major inconsistency in the reported terminology for CBCT properties and settings and that there is a lack of evidence-based data on the radiation dose for CBCT imaging."[4] In any case, one thing is certain: patients undergoing CBCT scans are being exposed to ionizing radiation.

Exposure to ionizing radiation increases cancer risk in humans, particularly in children.[5,10] Thus it is important for clinicians to minimize the radiation that patients are exposed to. This is particularly true in the field of orthodontics where many patients are children and young adults. It is important to note that radiographic images providing benefits that outweigh the risks of radiation exposure are considered acceptable by the health professions.[11] This has led health professionals to adopt the “As Low As Reasonably Achievable” (ALARA) principle.[10] The ALARA principle requires a risk/benefit decision to be made by the clinician and the risks and benefits of this decision to the patient should not be analyzed separately from one another.[12] Because the amount of radiation patients are exposed to from a CBCT scan is significantly higher than exposure from conventional orthodontic radiography, the clinician must make such a decision regarding CBCT use.[13]

The data from a study performed by Brooks et al., can help inform this decision by providing a comparison between CBCT scans and conventional radiography used in orthodontics. A panoramic radiograph has an effective radiation dose of 5.5 to 22.0 microsieverts. A lateral cephalogram exposes the same patient to 2.2 to 3.4 microsieverts of effective radiation dose. In comparison, a CBCT scan results in an effective radiation dose of 58.9 to 1025.4 microsieverts.[12] Another study measured a range of 68 to 1073 microsieverts of effective dose radiation delivered to patients during CBCT scans.[13] Does the diagnostic value and/or difference in treatment outcome from use of a CBCT scan justify exposing patients to extra radiation for routine orthodontic cases? For complex cases? Some studies suggest that further research regarding patient outcomes is necessary to answer these questions.[7,10] However, there is no “safe” dose of radiation and any exposure can lead to cancer-causing effects.[14] The American Dental Association

(ADA) released a statement on December 5, 2012 highlighting the need for adherence to the ALARA principle among dental practitioners:

> "The ADA's 'Dental Radiograph Examinations: Recommendations for Patient Selection and Limiting Radiation Exposure' are intended to be used in conjunction with dentists' professional judgment to determine whether and when dental x-rays are needed. Dental x-rays help dentists evaluate and diagnose oral diseases and conditions, but the ADA recommends that dentists weigh the benefits of taking dental x-rays against the possible risk of exposing patients to the radiation from x-rays, the effects of which can accumulate from multiple sources over time. 'As doctors of oral health, dentists are in the best position to make decisions on whether to prescribe dental x-rays after an oral examination and with consideration of the patient's health history. Prescribing dental x-rays should be an individualized process,' said ADA President Robert A. Faiella, D.M.D., M.M.Sc. Since 1989, the ADA has recommended the ALARA principle in relation to dental x-rays—that radiation exposure to patients is 'as low as reasonably achievable.'"[15]

A joint statement regarding the use of CBCT in orthodontics was released by The American Association of Orthodontists (AAO) and the American Academy of Oral and Maxillofacial Radiology (AAOMR) in August, 2013. The statement includes specific recommendations for CBCT use adhering to the ALARA principle:

> "The choice of radiographic examination in orthodontics, and CBCT in particular, should be based on initial clinical evaluation and must be justified based on individual need. The benefits to the patient of each exposure must outweigh the radiation risks. CBCT is a supplement to two-dimensional radiographic imaging in most situations. Exposure of patients to ionizing radiation must never be considered as 'routine.' A CBCT examination should never be performed without initially obtaining a thorough clinical examination. The AAO/AAOMR Joint Task Force Committee provides numerous general and specific recommendations for CBCT in orthodontic practice categorized under four guidelines: 1) Image appropriately by applying imaging selection criteria, 2) Assess the radiation dose risk, 3) Minimize patient radiation exposure and, 4) Maintain professional competency in performing and interpreting CBCT studies."[16]

It is clear that CBCT should be used sparingly and only with justification in the field of orthodontics. This may limit the number of patients on which 3D imaging from CBCT will be available.

MR is an alternative 3D imaging technology available to orthodontists. MR does not expose patients to ionizing radiation and is associated with no known ionizing radiation hazards.[17] Thus, multiple 3D images may be taken without concern for radiation exposure using MR technology. Furthermore, MR images allow for soft-tissue analysis that is impossible with CBCT imaging.[18] A study comparing the accuracy of MR and CBCT images showed that there is no significant differences between linear measurements between the two imaging methods.[19] Assuming that the CBCT measurements in the study are correct, the study concluded that MRI images show accurate 3D linear measurements.

There are also some disadvantages to MR imaging use in orthodontics. Foremost among these is limited access to and availability of MR scanners. Additionally, MR imaging takes longer than some other forms of 3D imaging, cannot be used on claustrophobic patients, and does not image hard tissues well. Another disadvantage is that MR uses magnetic fields in order to create images. These magnetic fields can be disrupted by stainless steel orthodontic appliances and can make MR imaging difficult in orthodontic patients with fixed metal appliances.[1] Due to concerns that overheating and deflection of metallic materials such as orthodontic brackets and wires could be harmful to orthodontic patients during MR scans, one study tested these things, but determined that such concerns were unfounded.[20]

Some progress has been made in minimizing these disadvantages. According to Gorgulu et al, if MR is to be performed during orthodontic treatment for imaging of structures non-adjacent to orthodontic appliances it is not necessary to remove brackets.[21] However, stainless steel and nickel titanium wires should be removed prior to MR imaging on orthodontic patients.[20] Despite being unable to image hard tissues well MR imaging has been shown to be effective for localizing impacted teeth based on contrasts between teeth and surrounding tissues such as gums, tongue, cheek, saliva, and marrow of jaw bones visible on MR images.[22] Furthermore, a technique called contrast-enhanced MR has been developed to allow better visualization of teeth within the oral cavity.[23] There is also evidence to show that the availability of MR scanners is increasing and the cost of MR scans is decreasing.[18] When ceramic orthodontic brackets are used, there is no distortion of MR images. However, when metallic slots are present within ceramic brackets distortion still occurs. The use of ceramic brackets could make MR scans a viable method of orthodontic imaging before, during, and after orthodontic treatment.[20]

Diagnostic imaging is important in the field of orthodontics for treatment planning. 3D imaging provides the highest level of diagnostic information. CBCT and MR imaging are methods that can be used for 3D orthodontic imaging. Risks associated with ionizing radiation make CBCT unsatisfactory as a 3D imaging method for all orthodontic patients. However, MR technology allows for 3D imaging without concern over negative side effects to patients from ionizing radiation. There are disadvantages to MR imaging including high cost and limited availability, long scanning time, inability to use on claustrophobic patients, and difficulty imaging metal materials. If continued progress can be made to eliminate these issues MR provides the safest method of 3D imaging for orthodontic patients. Based on the ALARA principle, MR should become the method of choice for 3D imaging amongst orthodontists.

Significance of the Study

Ionizing radiation is linked to an increase in the risk for cancer.[11] Children and adolescents are particularly susceptible to this risk due to their growing tissues being more radio-sensitive.[10] Many orthodontic patients are growing and thus the risk of cancer from ionizing radiation is of particular importance in the field of orthodontics. To minimize cancer risk from ionizing radiation the as low as reasonably achievable (ALARA) principle has been adopted for dental radiology. However, accurate orthodontic diagnosis requires visualization of soft and hard tissue structures and often includes conventional radiographs and CBCT scans. Using MR imaging for orthodontic diagnosis adheres to the ALARA principle by enabling the discontinuation of radiographs which expose patients to ionizing radiation. Establishing that tooth-length measurements may be successfully made from MR scans is a first step toward showing that orthodontic diagnosis may be performed solely using imaging that does not expose patients to ionizing radiation.

Hard tissues including cortical bone and teeth appear black on MR images due to their lack of proton content. Previous studies have shown that accurate localization of teeth is possible when proton-rich materials such as saliva and highly vascular cancellous bone surround the crowns of the teeth.[19,22] However, areas of contact between teeth and between teeth and cortical bone may cause difficulty in visual differentiation.[24] By surrounding teeth with a proton-rich contrast medium, this problem may be reduced or eliminated. With a contrast medium in place during MR scans there will be a thin area of proton-rich material appearing light on MR images separating the dark-appearing proton-poor teeth from one another and increasing visualization. For this study, alginate impression material will be used as the proton-rich contrast medium. This study will determine if using alginate around the teeth during MR scans allows for easier determination of tooth landmarks and more accurate tooth-length measurements.

Null Hypotheses

1. There is a difference between tooth lengths measured on CBCT images and MR images without alginate bite registration.
2. There is a difference between tooth lengths measured on CBCT images and MR images with alginate bite registration.
3. There is a difference between tooth lengths measured on MR images without alginate bite registration and MR images with alginate bite registration.

CHAPTER TWO

CORRELATION OF TOOTH LENGTH MEASUREMENTS MADE ON CBCT AND 3T MR IMAGES

Abstract

Objective. This study compared tooth length measurements made on cone beam computed tomography (CBCT) scans and 3-Tesla (3T) magnetic resonance (MR) scans performed with and without an alginate bite registration surrounding the crowns of the teeth.

Materials and Methods. One CBCT scan, one MR scan with alginate bite registration, and one MR scan without bite registration were performed on 12 subjects. The alginate bite registration was used to provide a proton-rich material to surround proton-poor teeth in an attempt to improve visualization of teeth. DICOM formatted images from each of the three scans for each subject were oriented in all three planes of space. Slices of 4 mm thickness were made through all permanent teeth. Tooth length measurements were made from the slices.

Results. The presence of alginate bite registration during MR scans made it impossible to determine tooth lengths on MR images. Tooth lengths measured from CBCT and MR scans without alginate bite registration were very highly correlated. For 336 measurements ($N = 336$) the correlation coefficient was found to be 0.953 ($p < 0.001$).

Conclusions. 1.) Alginate is not a useful material in increasing visualization of teeth on MR scans. 2.) Tooth length measurements made on MR scans are highly correlated with tooth length measurements made on CBCT scans.

Introduction

Orthodontists use radiographs for the purposes of diagnosis and treatment planning. These images generally include lateral cephalograms, panoramic radiographs, and full mouth surveys including multiple periapical and bitewing images. Recently, these have been increasingly supplemented by three-dimensional (3D) imaging technologies, in particular cone beam computed tomography (CBCT).[1,2,3,4] CBCT images have been shown to be highly accurate and useful for orthodontic diagnosis and treatment planning.[5,6,7,8]

In addition to diagnostic records it is also necessary for orthodontists to take supplementary cephalograms, panoramic x-rays, and periapical images during the course of treatment to evaluate progress. Final orthodontic treatment records also include radiographs. Each radiograph taken exposes orthodontic patients to ionizing radiation.[9] When CBCT scans are used patients are exposed to potentially large amounts of additional ionizing radiation.[10,11,12] This has led to concern over the amount of ionizing radiation that orthodontic patients are being exposed to, particularly since many orthodontic patients are children and adolescents with quickly growing tissues that are more susceptible to the deleterious effects of ionizing radiation.[10,11]

Weighing the risks from ionizing radiation versus the benefit of radiographs is an important consideration for orthodontists as well as other medical professionals.[12,13,14,15] The American Dental Association (ADA) recommends that radiation exposure to patients should be kept as low as reasonably achievable (ALARA).[15] A joint statement by the American Association of Orthodontists (AAO) and the American Academy of Oral and Maxillofacial Radiology (AAOMR) provides guidelines for the use of CBCT in orthodontics: "CBCT … should be based on initial clinical evaluation and must be justified based on individual need. The benefits of each exposure must outweigh the radiation risks."[16]

Magnetic resonance (MR) imaging is a technology that allows 3D visualization of the head and neck without exposing patients to ionizing radiation.[17] In addition to providing images of hard tissues as with conventional radiographs, MR also allows excellent visualization of soft tissues such as the temporomandibular joint (TMJ), articular disk, and pharyngeal airway.[17,18] Studies have shown that MR imaging is useful for visualizing teeth,[23] measuring tooth lengths,[24] and localizing impacted teeth.[22] MR images have been shown to provide, "excellent dimensional accuracy" when superimposed on CBCT images.[19] There is also evidence that MR may be used for progress records during orthodontic treatment with ceramic brackets or plastic aligners.[20,21]

Despite its advantages, many orthodontists have shied away from MR imaging due to perceived difficulties visualizing hard tissues such as teeth.[23] In particular it can be difficult to differentiate teeth from one another at points of occlusion due to the teeth appearing black on MR images.[24] Surrounding teeth in a proton-rich medium that appears white on MR images may increase visualization of teeth.[23] Alginate is a proton-rich medium that may be used to surround teeth during MR scans. The purpose of this study is to determine if measurements of tooth lengths made on CBCT images correlate with measurements of tooth lengths made on MR images with and without the use of an alginate bite registration. Tooth length measurements on all three scans will be compared to determine if alginate bite registration increases visualization of teeth on MR scans allowing for increased accuracy of measurement.

Null Hypotheses

1. There is a difference between tooth lengths measured on CBCT images and MR images without alginate bite registration.
2. There is a difference between tooth lengths measured on CBCT images and MR images with alginate bite registration.
3. There is a difference between tooth lengths measured on MR images without alginate bite registration and MR images with alginate bite registration.

Materials and Methods

This study was performed on thirteen human subjects. The rights of the human subjects were protected and approval for this study was granted by the Institutional Review Board (IRB) of Loma Linda University. Each subject was a new patient start in the Loma Linda University School of Dentistry (LLUSD) graduate orthodontics clinic. Patients were selected from consecutive starts based on lack of exclusion criteria and their willingness to participate in the study. Exclusion criteria was the presence of: 1) metal dental restorations, 2) dental implants, 3) fixed orthodontic appliances, 4) removable orthodontic appliances, 5) pacemakers, 6) cochlear implants, 7) metal foreign bodies in the eyes, 8) aneurysm clips, 9) prosthetic metal implants, and 10) pregnancy. During data collection one subject was eliminated due to movement artifacts present on CBCT scan. Ages of remaining patients ranged from 12 years and 1 month to 31 years and 5 months. Average age was 15 years and 11 months. Median age was 12 years and 9 months. Seven subjects were male. Five subjects were female.

Each subject underwent one CBCT scan as part of diagnostic records for orthodontic treatment. Additionally subjects underwent two MR scans for the purpose of this study. The CBCT scan and first MR scan were performed with no bite registration. For the second MR scan an alginate bite registration was taken, trimmed, and replaced in the patient's mouth. Bite registrations were performed with Alfa Triple Trays (Patterson Dental, St. Paul, Minnesota, USA). Excess alginate was removed in locations not surrounding teeth including the palate and area posterior to the most distal tooth. During trimming of the bite registration patients rinsed with water to remove excess alginate. All scans were performed within two weeks of one another and prior to the placement of orthodontic separators or appliances.

The scanner used for whole head CBCT imaging was a NewTom 5G scanner (AFP Imaging, Elmsford, New York, USA). Settings used for the CBCT scan include an 18x16 inch field of view (FOV) and an exposure time of 5.4 seconds. Scans were taken with patients in a face-up supine position. Digital Imaging and Communications in Medicine (DICOM) formatted images were created from axial slices.

MR scans were performed with a 3.0T imaging system in a 12 channel head array coil (TIM/Trio, Siemens Medical Solutions, Erlangen, Germany). Scan time was 4-5 minutes. Contiguous sagittal images of the whole head were created with a T1-weighted 3D imaging sequence (Magnetization Prepared Rapid Acquisition by Gradient Echo (MP-RAGE), TR/TE = 1950/2.26ms) and isotropic resolution of 1.0x1.0x1.0mm. MR scans were constructed in DICOM format for comparison with CBCT DICOM volumes. Scans were reviewed for incidental pathology by a fellowship trained neuroradiologist. Osirix imaging software (Pixmeo, Geneva, Switzerland) was used for CBCT and MR DICOM orientation, evaluation, and measurement of tooth lengths. Volumes were initially oriented in three planes to reduce variability of measurements. First, volumes were oriented from the frontal view (coronal plane) such that a line connecting the lower rim of each orbit was parallel to the horizon (Fig. 1). Next, from a bottom up view (transverse plane) the volumes were oriented so that a line connecting the widest points of the maxillary sinuses was parallel to the horizon (Fig. 2). Third, the volumes were oriented from a side view (sagittal plane) such that a line connecting the anterior nasal spine (ANS) to posterior nasal spine (PNS) was parallel to the horizon (Fig. 3).

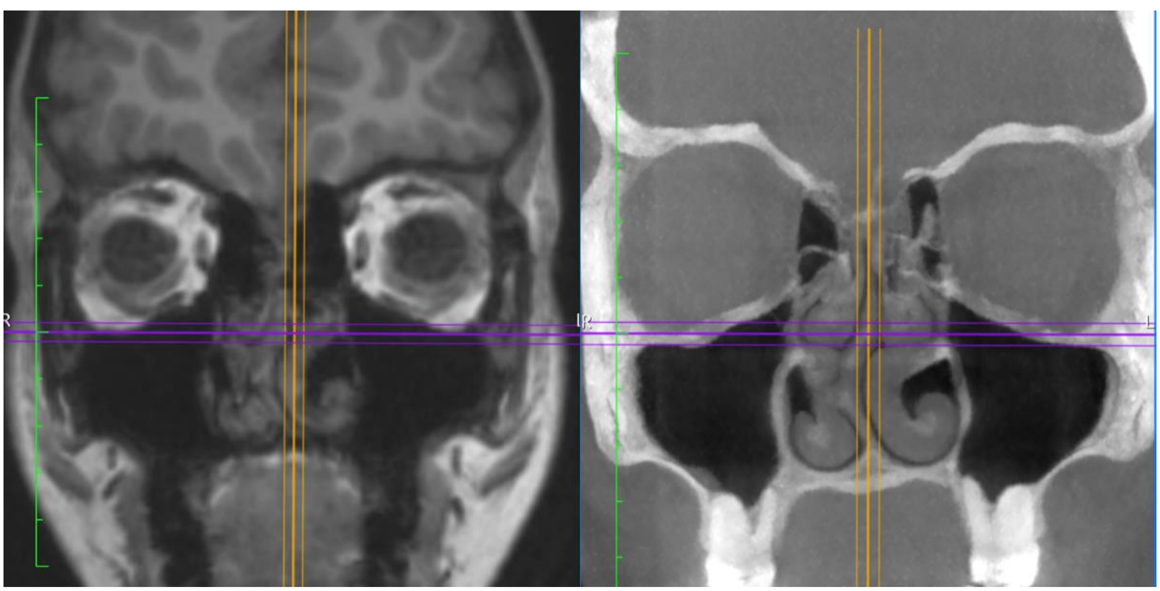

Figure 1. Orientation of the MR (left) and CBCT (right) DICOM volumes in the coronal plane. A line connecting the lowest point of each orbit was made parallel to the horizon.

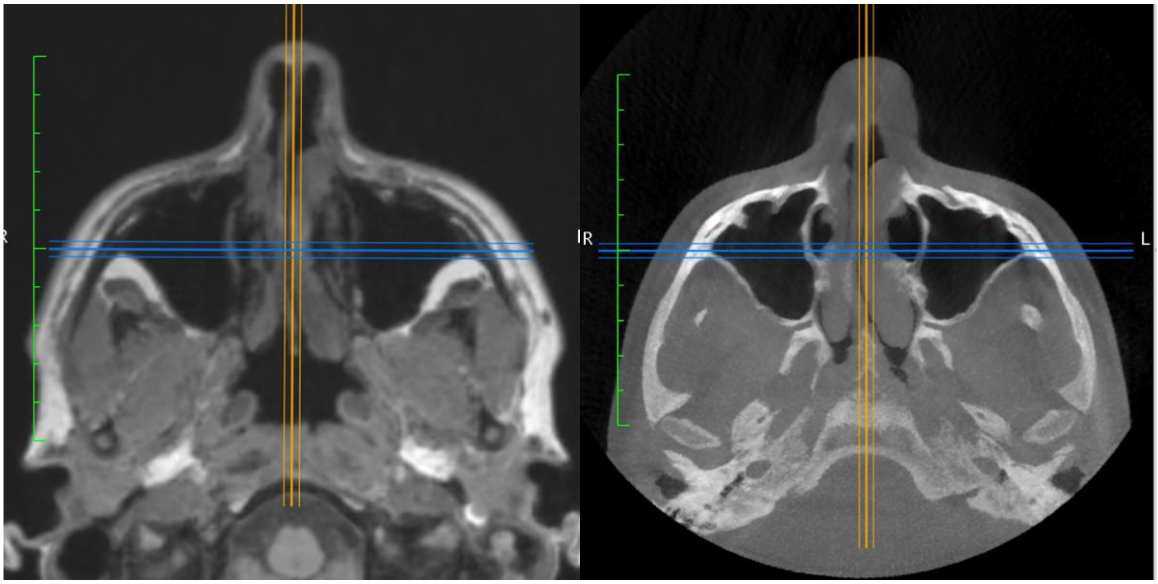

Figure 2. Orientation of the MR (left) and CBCT (right) DICOM volumes in the transverse plane. A line connecting the widest point of the maxillary sinuses was made parallel to the horizon.

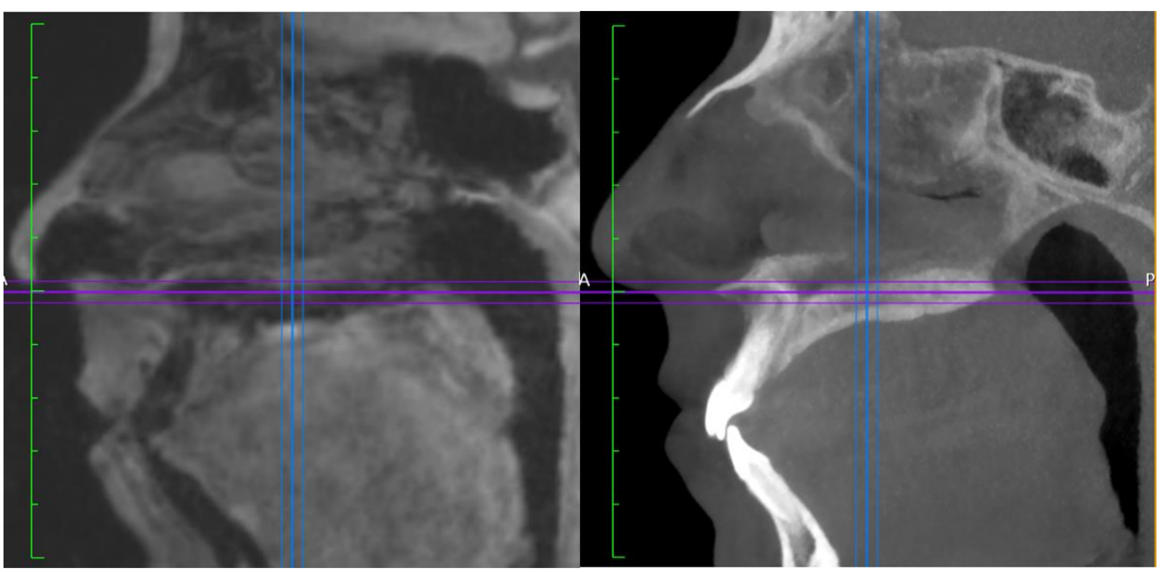

Figure 3. Orientation of the MR (left) and CBCT (right) DICOM volumes in the sagittal plane. A line connecting ANS-PNS was made parallel to the horizon.

Following volume orientation 4 mm thick slices were taken to measure tooth lengths. Using 4 mm thick slices was found to decrease variability in locating tooth landmarks because incisal edges, cusp tips, and most superior (maxillary arch) or inferior (mandibular arch) points on roots were contained within slices, even if slight orientation deviations occurred. Slices were aligned along the long axis of incisors through the center of the incisal edge and root apex and perpendicular to a line through the center of

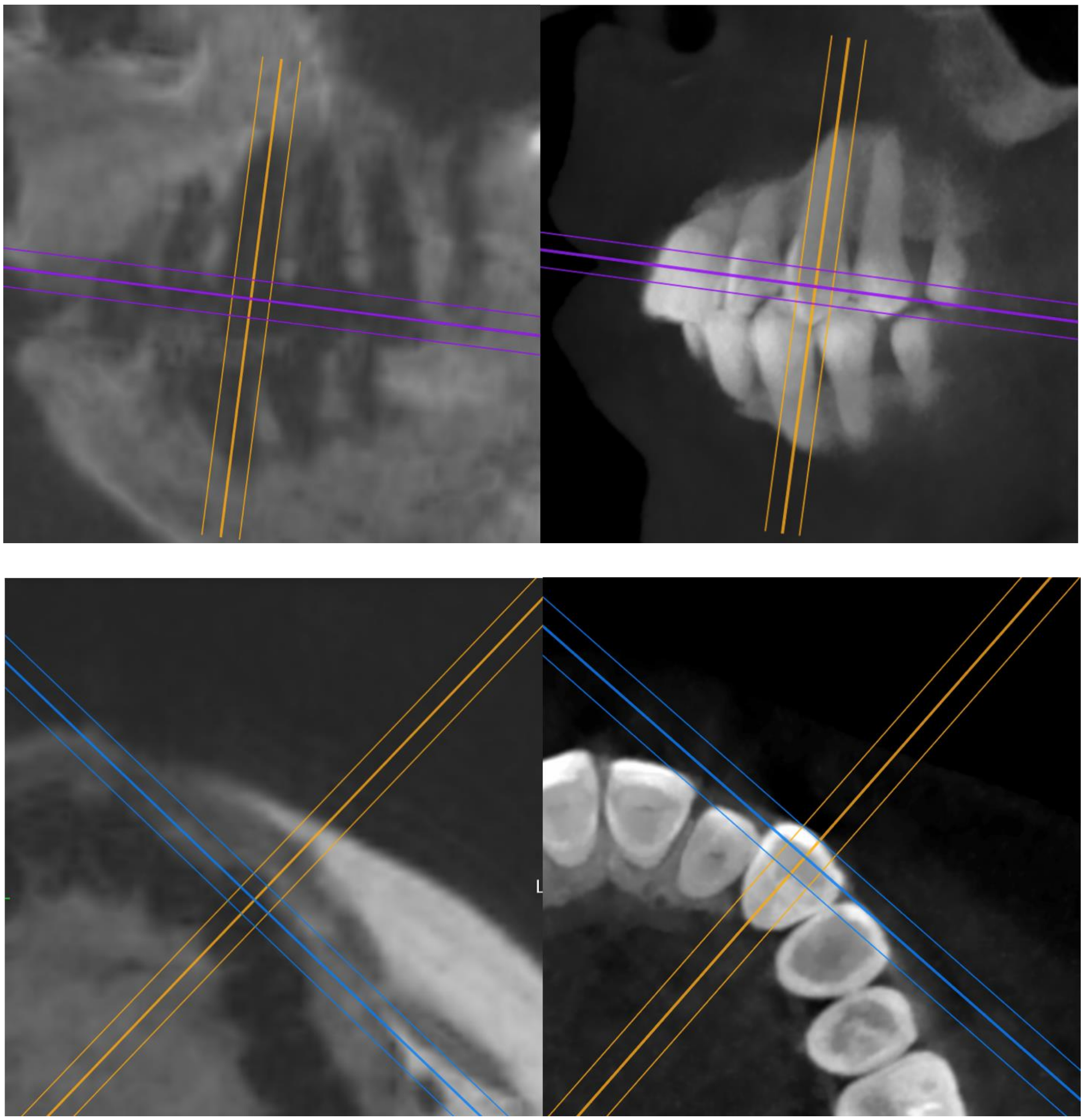

Figure 4. Slice orientation. Shown here is an upper left canine being oriented on MR (left) and CBCT (right). For canines slices were aligned through the cusp tip and root apex (top) and perpendicular to a line through the mesial and distal marginal ridges (bottom).

the incisal edge. For canines, slices were aligned through the cusp tip and root apex and perpendicular to a line through the mesial and distal marginal ridges and cusp tip (Fig. 4). Premolar slices were aligned through the buccal cusp tip and buccal root apex and perpendicular to a line through the central groove. For molars, slices were aligned through the mesiobuccal cusp tip and the mesial root apex and perpendicular to a line through the central groove. No orientation changes were made in a sagittal direction following volume orientation.

All permanent teeth except third molars were measured, including non-erupted teeth. No primary teeth were measured. Maxillary incisor teeth were measured from the most inferior point of the incisal edge to the most superior point of the root (Fig. 5). Mandibular incisor teeth were measured from the most superior point of the incisal edge to the most inferior point of the root. For maxillary canines, measurements were made from the most inferior point of the cusp to the most superior point of the root (Fig. 6). Mandibular canine measurements were made from the most superior point of the cusp to the most inferior point of the root. Premolar teeth were measured from the most inferior point of the buccal cusp to the most superior point of the buccal root on the maxillary arch (Fig. 7). On the mandibular arch, premolar teeth were measured from the most superior point of the cusp to the most inferior point of the root. Maxillary molars were measured from the most inferior point of the mesiobuccal cusp to the most superior point of the mesiobuccal root (Fig. 8). Mandibular molars were measured from the most superior point of the mesiobuccal cusp to the most inferior point of mesial root.

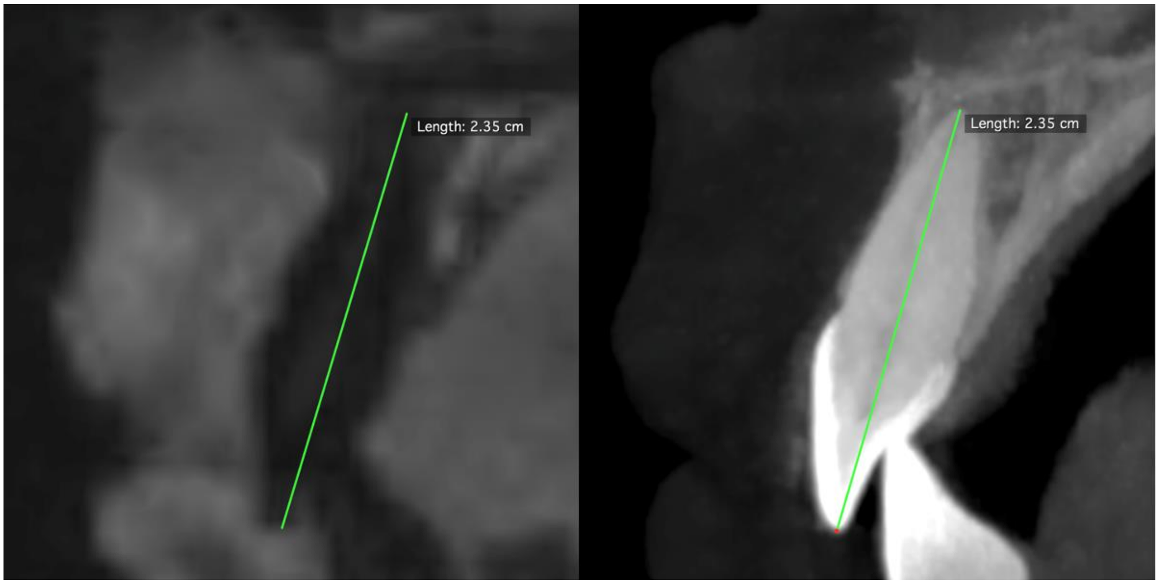

Figure 5. Measurement of an incisor. Shown here is a maxillary left central incisor on MR slice (left) and CBCT slice (right). Maxillary incisors were measured from the most inferior point on the incisal edge to the most superior point on the root.

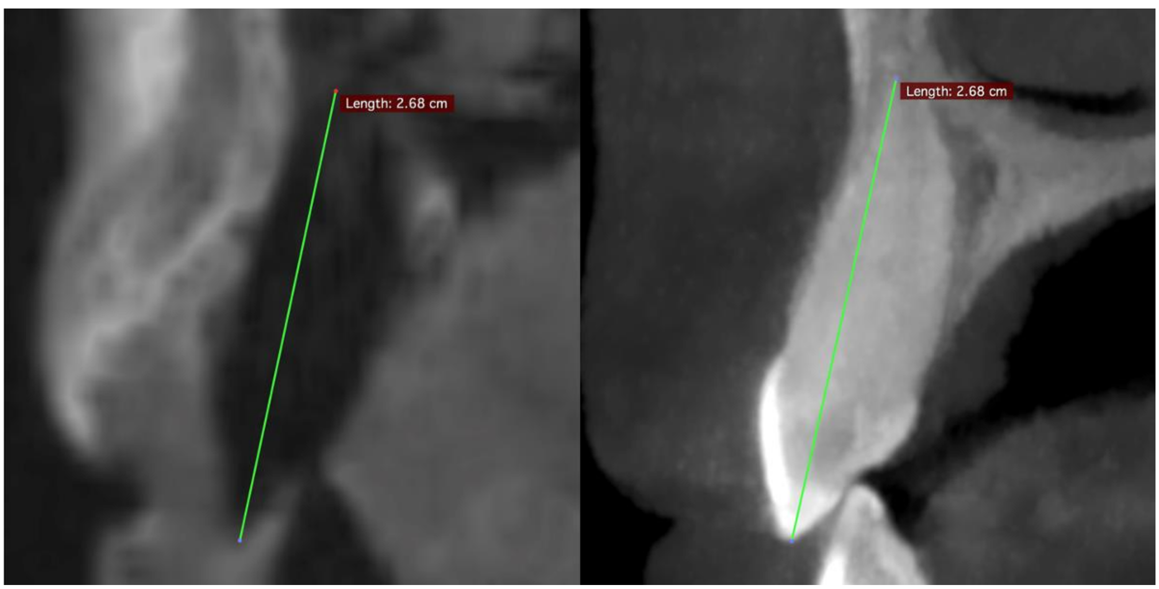

Figure 6. Measurement of a canine. Shown here is a maxillary left canine on MR slice (left) and CBCT slice (right). Maxillary canines were measured from the most inferior point on the cusp tip to the most superior point on the root.

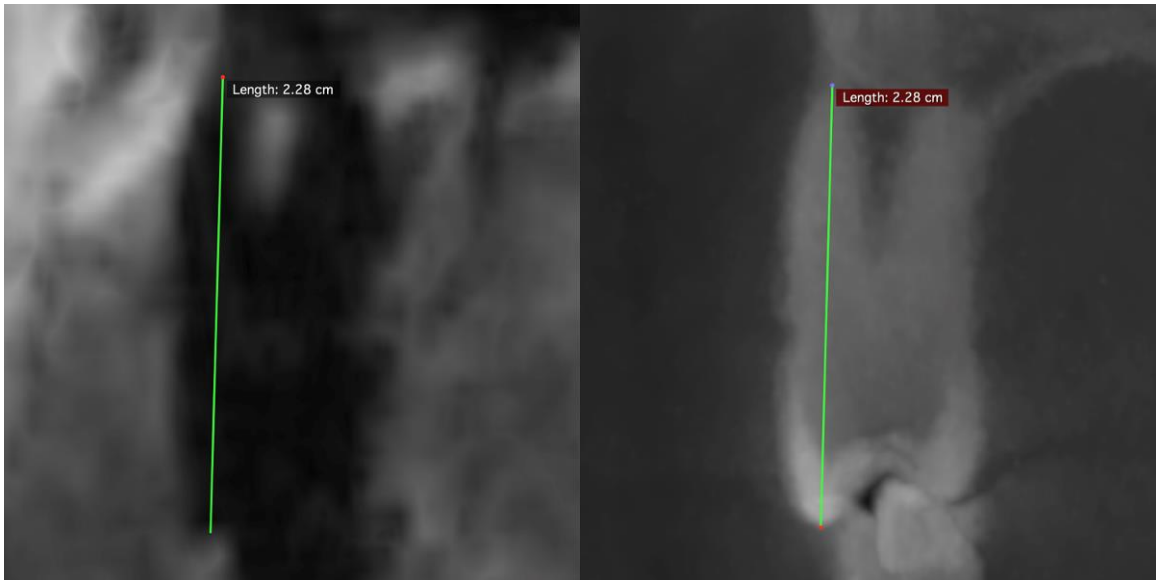

Figure 7. Measurement of a premolar. Shown here is a maxillary left first premolar on MR slice (left) and CBCT slice (right). Maxillary premolars with multiple roots were measured from the most inferior point on the buccal cusp tip to the most superior point on the buccal root.

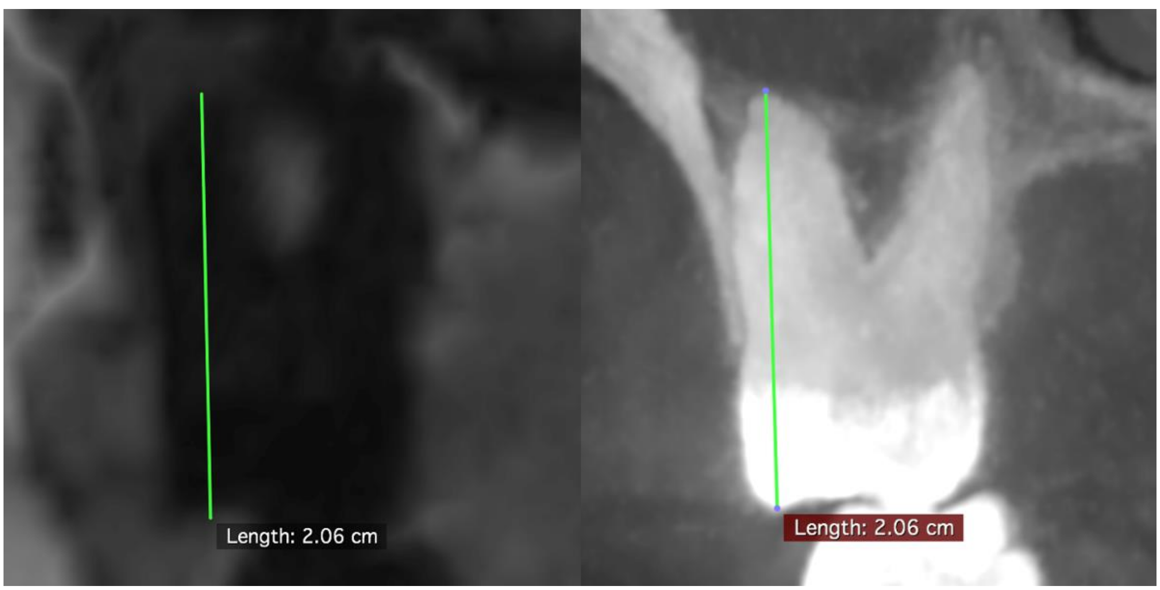

Figure 8. Measurement of a molar. Shown here is a maxillary left first molar on MR slice (left) and CBCT slice (right). Maxillary molars were measured from the most inferior point on the buccal cusp tip to the most superior point on the buccal root.

Results

Tooth length measurements from MR scans with alginate bite registration were not taken due to alginate material appearing black on MR images and obscuring view of the teeth (Fig. 9). These images were deemed not clinically acceptable for evaluation.

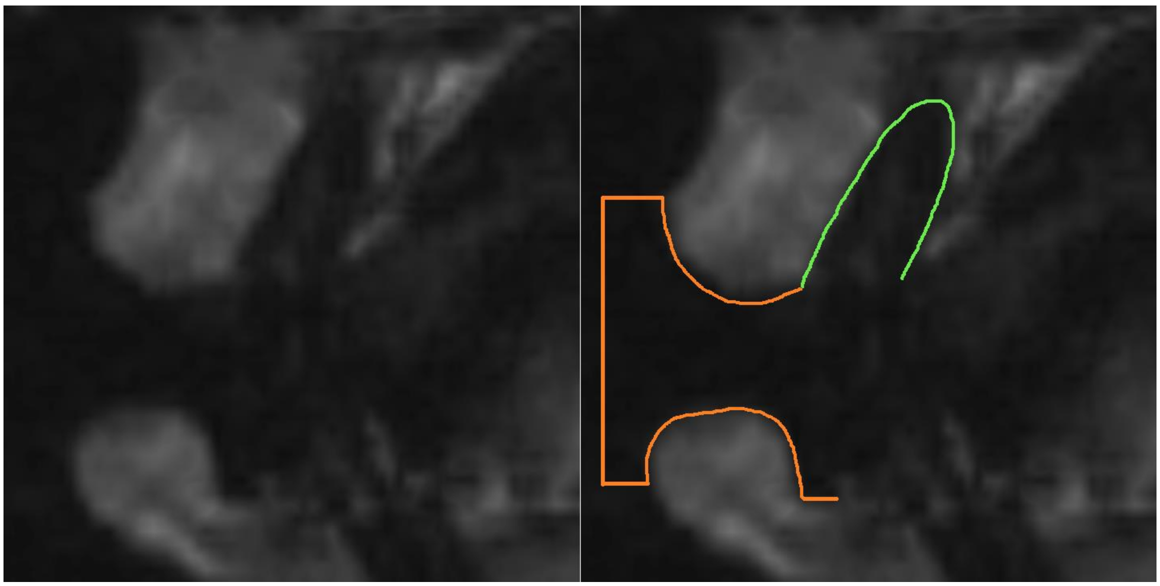

Figure 9. MR image from scan with alginate bite registration. Note the difficulty determining position of the crown of the upper left central incisor (left). On the right the root has been highlighted in green and the alginate tray with alginate material has been outlined in orange. Visualization of the incisal edge is impossible due to the alginate surrounding the crown appearing dark like the tooth.

A total of 336 tooth length measurements were taken (N = 336). Measurements taken from CBCT images for the maxillary and mandibular arches are shown in Table 1. Table 2 shows measurements taken from MR images. Of the 336 measurements 28 were taken on non-erupted teeth.

Table 1. Tooth length measurements made from CBCT images.

Maxillary Arch (cm)													
M2	M1	P2	P1	C	I2	I1	I1	I2	C	P1	P2	M1	M2
#2	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**#13**	**#14**	**#15**
1.82	1.95	1.86	2.02	2.79	2.30	2.42	2.30	2.32	2.75	2.02	2.02	1.89	1.81
1.51	1.86	1.74	1.95	2.30	2.08	2.21	2.23	2.10	2.39	1.88	1.78	1.77	1.49
2.09	2.45	2.45	2.59	3.34	2.89	2.94	2.90	2.87	3.18	2.68	2.51	2.31	2.24
1.53	2.15	2.25	2.26	2.86	2.72	2.91	2.61	2.74	2.81	2.32	2.29	2.22	1.60
1.89	1.96	1.95	2.23	2.76	2.56	2.70	2.61	2.46	2.68	2.14	2.08	1.98	1.86
1.79	1.76	1.86	1.97	2.41	2.29	2.22	2.28	2.23	2.42	2.06	1.94	1.75	1.92
1.64	2.04	1.74	1.96	2.43	2.37	2.32	2.32	2.32	2.47	2.20	1.82	2.07	1.60
1.77	1.94	1.94	1.96	2.71	2.50	2.29	2.10	2.35	2.72	1.93	1.92	1.98	1.98
1.68	2.15	2.25	2.21	2.76	2.32	2.60	2.64	2.42	2.74	2.23	2.15	2.09	1.74
1.18	1.96	1.27	1.48	1.90	1.55	2.47	2.51	1.64	1.85	1.35	1.15	1.96	1.08
2.03	1.86	2.27	2.17	2.90	2.33	2.43	2.38	2.24	3.16	2.23	2.04	1.84	2.06
1.95	2.06	1.91	2.82	2.61	2.23	2.32	2.27	2.24	2.66	2.25	2.21	1.96	1.86

Mandibular Arch (cm)													
M2	M1	P2	P1	C	I2	I1	I1	I2	C	P1	P2	M1	M2
#18	**#19**	**#20**	**#21**	**#22**	**#23**	**#24**	**#25**	**#26**	**#27**	**#28**	**#29**	**#30**	**#31**
1.83	2.01	1.86	2.11	2.34	1.99	1.74	1.74	1.98	2.59	2.08	1.74	2.07	1.81
1.59	1.91	1.74	1.88	2.18	2.06	2.03	1.92	2.02	2.17	1.79	1.80	2.06	1.68
2.09	2.30	2.49	2.53	3.15	2.55	2.62	2.42	2.59	3.12	2.64	2.42	2.30	2.10
1.79	2.18	2.21	2.21	2.56	2.46	2.40	2.55	2.54	2.62	2.22	2.16	2.21	1.74
1.92	2.18	2.19	2.22	2.59	2.40	2.34	2.34	2.35	2.65	2.15	2.19	2.19	1.92
1.67	1.75	1.62	2.04	2.35	2.12	1.91	1.85	2.01	2.41	1.97	1.67	1.80	1.70
1.16	2.20	1.74	2.08	2.49	2.36	2.39	2.44	2.39	2.58	2.08	1.79	2.20	1.56
2.11	2.11	1.92	2.18	2.63	2.16	2.03	1.98	2.24	2.59	2.23	1.95	2.11	1.79
1.84	2.10	2.23	2.27	2.53	2.31	2.12	2.23	2.50	2.60	2.18	2.15	2.05	1.83
1.15	2.15	0.99	1.24	1.86	2.49	2.57	2.58	2.45	1.86	1.30	1.00	2.04	1.08
2.10	1.90	2.08	2.20	2.54	2.19	2.13	2.14	2.16	2.55	2.17	2.09	1.96	2.08
1.86	2.13	1.94	2.32	2.56	2.42	2.33	2.38	2.34	2.56	2.37	2.15	2.18	1.99

Measurements that are highlighted in blue are non-erupted second molars. Measurements that are highlighted in green are non-erupted teeth that are not second molars.

Table 2. Tooth length measurements made from MR images without alginate bite registration.

Maxillary Arch (cm)

M2	M1	P2	P1	C	I2	I1	I1	I2	C	P1	P2	M1	M2
#2	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**#13**	**#14**	**#15**
1.86	1.92	1.83	2.08	2.71	2.36	2.40	2.35	2.36	2.75	2.05	2.04	1.97	1.89
1.44	1.92	1.82	1.90	2.38	2.11	2.19	2.23	2.03	2.47	1.83	1.76	1.85	1.60
2.21	2.45	2.38	2.68	3.14	2.69	2.89	2.93	2.88	3.11	2.62	2.44	2.42	2.18
1.44	2.20	2.32	2.37	2.84	2.83	2.90	2.57	2.70	2.88	2.28	2.37	2.12	1.66
1.89	1.93	2.06	2.22	2.67	2.50	2.67	2.65	2.25	2.78	1.97	2.11	2.07	1.91
1.86	1.84	1.90	1.93	2.41	2.26	2.17	2.21	2.30	2.52	1.98	1.98	1.84	2.13
1.69	2.03	1.83	2.05	2.39	2.20	2.25	2.30	2.26	2.44	2.17	1.89	2.15	1.65
1.83	1.99	1.92	1.90	2.65	2.36	2.22	2.18	2.38	2.64	1.89	2.01	2.07	2.07
1.75	2.17	2.29	2.30	2.89	2.27	2.66	2.67	2.55	2.64	2.74	2.04	2.12	1.61
1.27	2.15	1.05	1.34	2.06	1.59	2.25	2.52	1.51	1.95	1.02	1.19	1.79	1.36
2.01	1.93	2.36	2.18	2.58	2.36	2.36	2.22	2.29	2.79	2.23	2.13	1.89	1.98
1.87	2.10	2.04	2.77	2.67	2.36	2.23	2.32	2.26	2.74	2.31	2.17	2.07	1.92

Mandibular Arch (cm)

M2	M1	P2	P1	C	I2	I1	I1	I2	C	P1	P2	M1	M2
#18	**#19**	**#20**	**#21**	**#22**	**#23**	**#24**	**#25**	**#26**	**#27**	**#28**	**#29**	**#30**	**#31**
1.82	2.07	2.05	2.28	2.68	1.96	1.84	1.75	2.05	2.70	2.22	1.98	2.06	1.77
1.53	1.80	1.79	1.87	2.25	2.03	2.05	1.97	2.16	2.10	1.99	1.75	2.04	1.65
2.03	2.22	2.45	2.52	3.08	2.63	2.62	2.55	2.71	3.16	2.62	2.33	2.38	2.10
1.87	2.12	2.27	2.47	2.69	2.48	2.60	2.57	2.60	2.56	2.19	2.05	2.21	2.03
2.04	2.34	2.24	2.29	2.63	2.34	2.50	2.33	2.58	2.64	2.26	2.22	2.32	2.05
1.89	1.96	1.84	2.16	2.50	2.05	1.98	1.83	1.92	2.57	1.92	1.74	1.81	1.79
1.21	2.20	1.78	2.02	2.47	2.26	2.36	2.48	2.35	2.56	2.00	1.72	2.36	1.53
2.03	2.17	1.89	2.24	2.62	2.27	2.14	2.07	2.07	2.70	2.29	2.02	2.22	1.97
1.89	2.31	2.19	2.21	2.37	2.32	2.58	2.33	2.38	2.59	2.23	2.14	2.31	1.86
1.28	2.15	1.06	1.41	1.88	2.56	2.46	2.54	2.52	1.96	1.46	1.20	2.18	1.22
2.18	2.06	1.88	2.16	2.67	2.01	2.27	2.22	2.41	2.51	2.09	2.11	2.01	2.13
1.92	2.15	2.06	2.39	2.61	2.47	2.20	2.10	2.39	2.57	2.36	2.16	2.19	2.08

Measurements that are highlighted in blue are non-erupted second molars. Measurements that are highlighted in green are non-erupted teeth that are not second molars.

A Kolmogorov-Smirnov test was performed to analyze the distribution of data. For CBCT the data was non-normally distributed (sig = 0.036). The MR data was also non-normally distributed (sig = 0.037). Due to the data being non-normally distributed, Spearman's Rho correlation was used in addition to Intraclass Correlation Coefficient (ICC) to analyze the combined data. Agreement between tooth length measurements made on CBCT and MR images was very high for both tests. Spearman's Rho was 0.953 (P <0.001) and ICC was 0.956 (P <0.001). The difference between MR and CBCT measurements were also compared (Fig. 10). Differences between the two imaging modalities were very small. The mean difference was 0.03 mm with a standard deviation of 0.11 mm.

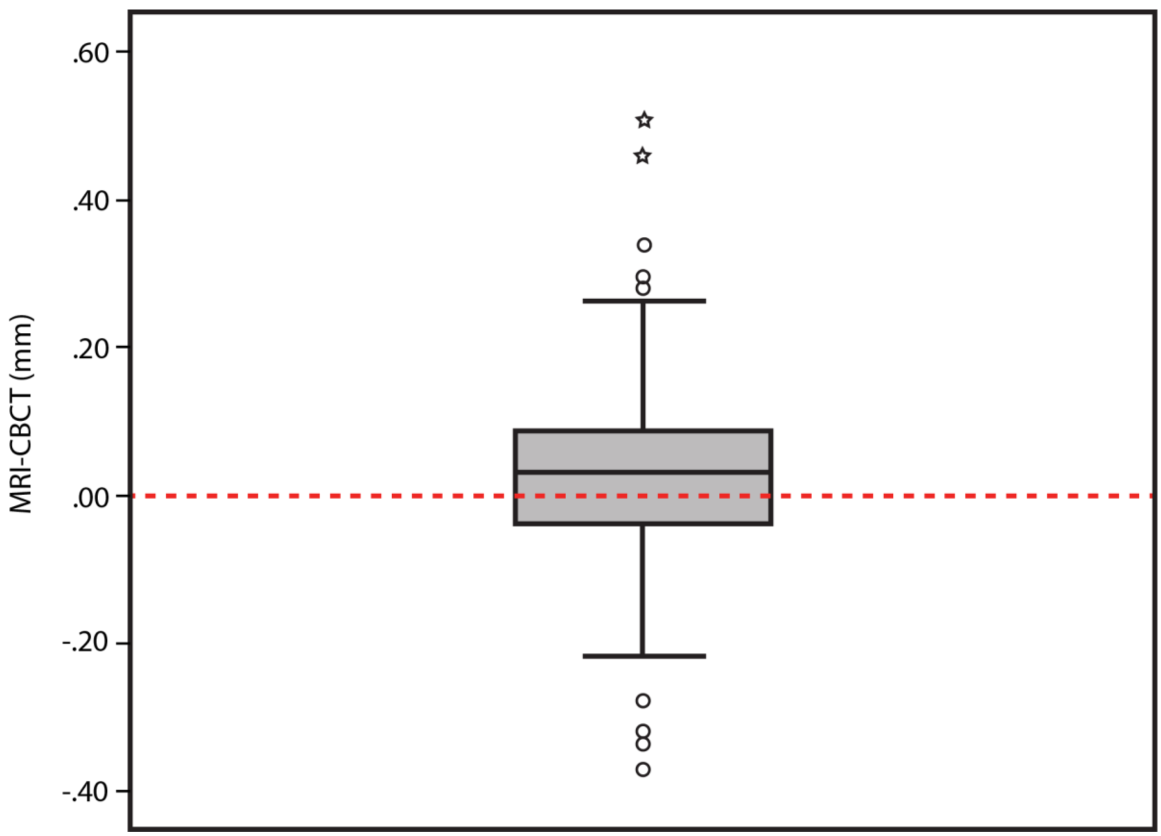

Figure 10. Differences between MR and CBCT measurements.

Table 3. Intraclass Correlation Coefficients for all teeth, maxillary and mandibular arches, tooth types, and erupted and non-erupted teeth.

Category	ICC	Mean Difference MRI – CBCT	SD of Differences	Sig
All Teeth	0.956	0.03	0.11	< 0.001
Maxillary Arch	0.965	0.05	1.05	< 0.001
Mandibular Arch	0.945	0.45	1.07	< 0.001
All Central Incisors	0.916	0.11	1.13	< 0.001
All Lateral Incisors	0.923	0.01	1.06	< 0.001
All Canines	0.922	0.10	1.22	< 0.001
All First Premolars	0.926	0.23	1.26	< 0.001
All Second Premolars	0.957	0.28	0.95	< 0.001
All First Molars	0.824	0.54	0.87	< 0.001
All Second Molars	0.927	0.50	0.94	< 0.001
Erupted Teeth	0.940	0.24	1.06	< 0.001
Non-Erupted Teeth	0.902	0.35	1.31	< 0.001

Reliability of measurements was tested by re-measuring tooth lengths for three subjects on CBCT and MR images three weeks after the original measurements. Reliability was very high for both modalities. For CBCT the ICC was 0.998 ($P < 0.001$). For MR the ICC was 0.970 ($P < 0.001$).

Results were further broken down into maxilla vs. mandible, tooth type, and erupted vs. non-erupted (Table 3). Individual teeth were also compared (Table 4). Measurements in the maxilla and mandible were both highly correlated with the mandible showing slightly less agreement (ICC 0.945, $P < 0.001$) than the maxilla (ICC 0.965, $P < 0.001$). First molar measurements showed the least agreement of any tooth category with ICC 0.824 ($P < 0.001$). Measurements of second premolars showed the most agreement of any tooth category with ICC 0.957 ($P < 0.001$). For individual teeth, ICC ranged from 0.704 (P <0.01) for tooth #19 to 0.980 (P <0.001) for tooth #13. Agreement was slightly lower for non-erupted teeth (ICC 0.902, P <0.001) than for erupted teeth (ICC 0.940, P <0.001).

Table 4. Intraclass Correlation Coefficients for individual tooth numbers.

Tooth Number	ICC	Mean Difference MRI – CBCT	SD of Differences	Sig
2	0.963	0.20	0.71	< 0.001
3	0.921	0.41	0.60	< 0.001
4	0.959	0.26	0.98	< 0.001
5	0.978	0.08	0.79	< 0.001
6	0.914	-0.32	1.36	< 0.001
7	0.947	-0.21	1.07	< 0.001
8	0.952	-0.53	0.66	< 0.001
9	0.963	0.00	0.66	< 0.001
10	0.961	-0.13	0.94	< 0.001
11	0.916	-0.10	1.37	< 0.001
12	0.879	-0.17	1.94	< 0.001
13	0.980	0.18	0.65	< 0.001
14	0.848	0.45	0.88	< 0.001
15	0.900	0.60	1.15	< 0.001
18	0.953	0.48	0.89	< 0.001
19	0.704	0.53	1.11	0.002
20	0.952	0.41	1.12	< 0.001
21	0.930	0.62	1.03	< 0.001
22	0.901	0.56	1.26	< 0.001
23	0.923	-0.11	0.84	< 0.001
24	0.796	0.83	1.57	< 0.001
25	0.935	0.14	1.06	< 0.001
26	0.831	0.48	1.32	< 0.001
27	0.966	0.27	0.76	< 0.001
28	0.947	0.37	0.97	< 0.001
29	0.950	0.26	1.08	< 0.001
30	0.754	0.77	0.86	< 0.001
31	0.905	0.75	0.99	< 0.001

Discussion

One purpose of this study was to determine if placing an alginate bite registration around crowns of the teeth during MR scans increased visualization of teeth and allowed for more accurate tooth length measurements to be made on MR images. It was discovered that alginate appears dark on MR images. This made alginate indistinguishable from teeth, which also appear dark on MR images. The alginate obstructed view of the teeth and made identification of landmarks necessary for measuring tooth lengths impossible to identify. It was deemed not clinically acceptable to make measurements on the MR images from scans with alginate bite registration in place.

While alginate bite registration did not help increase visualization of teeth, MR scans without alginate bite registration provided images that were suitable for tooth length measurements. Measurements made on these images were highly correlated with equivalent measurements taken from CBCT images. These findings suggest that MR imaging may be useful in orthodontic diagnosis and provide evidence that the technique should be further explored. For example, further studies may be undertaken to determine if MR images can be useful in other areas of orthodontic diagnosis such as cephalometric analysis.

This study has established a protocol that may be followed to determine if proton-rich materials other than alginate may be useful as a bite registration during MR scans to increase accuracy of tooth length measurements. Possibilities for proton-rich material include water, foam soaked in water, toothpaste, glycerin, or other liquid, gel or semi-solid materials. Finding a material that provides increased visualization of teeth may make even more accurate tooth length measurements possible. Particularly on teeth that showed lower ICC values such as first molars. Along with this study, such future studies may provide a basis for using MR as a non-ionizing alternative to CBCT scans for 3D imaging in orthodontics.

In addition to being successful in measuring tooth lengths on CBCT and MR images with a very high correlation, this study provided a method of orientation and measurement of tooth lengths that was shown to be reproducible. Reliability data suggests that measurements made by this method are highly repeatable when performed multiple times.

A study by Murray et al., also studied tooth lengths on MR images. Results were broken down by arch sextant and by individual tooth. For each sextant, tooth length measurements made on MR images were "almost perfect" (ICC 0.81 – 1.00) in correlation with those made on CBCT images, except the mandibular anterior sextant which resulted in only moderate correlation (ICC 0.499). Correlations for individual teeth ranged from ICC 0.961 in tooth number 13 to ICC 0.192 in tooth number 25.[20] The current study showed on average a higher correlation between tooth length measurements made on CBCT and MR images than were found in the previous study. Additionally, the range of measurements was smaller for the current study, with the highest ICC of 0.957 for tooth number 13 and the lowest ICC of 0.704 for tooth number 19. Reasons for the difference in ICC for the two studies may be a result of different volume orientation, slice thickness and orientation, and tooth measurement methods. Overall the protocol for the current study appears to be a more accurate method of measuring tooth lengths.

Conclusion

- The alginate method used in this paper is not a useful means to increase visualization of teeth on MR scans.
- Tooth length measurements made on MR scans are highly correlated with tooth length measurements made on CBCT scans. For this study the Intraclass Correlation Coefficient for 336 measurements was 0.953 ($P < 0.001$).

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CHAPTER THREE

EXTENDED DISCUSSION

While this study showed that tooth length measurements made from MR images can be highly correlated with the same measurements made on CBCT images, it should be noted that making the measurements on MR images is more difficult than making them on CBCT images. In order to define tooth landmarks for measurement on MR it was necessary to adjust the contrast of the image and search for landmarks such as pulp tissue and/or the crowns of opposing teeth. These factors resulted in considerably greater amounts of time taken measuring tooth lengths on MR images than on CBCT images and more uncertainty if landmarks on MR images had been correctly identified. Furthermore, there is a learning curve to correctly measuring teeth on MR images that is not present while measuring tooth lengths on CBCT images. Making accurate tooth length measurements on MR images has a feeling of being a learned skill, whereas making tooth length measurements on CBCT is more of an intuitive process. Finding a proton-rich contrast medium to highlight crowns of teeth may help to decrease this uncertainty. However, there may still be some difficulty identifying the roots of teeth on MRI images; particularly in areas of the thick cortical bone.

There are several ways in which this study was successful that were not discussed above. This study was successful was in creating relationships between the LLUSD Orthodontics and Dentofacial Orthopedics department and the radiology department at the Loma Linda University Medical Center (LLUMC). A major part of gathering data for this study was setting up the logistics of allowing new orthodontic patients to receive MR scans at LLUMC. Now that these relationships have been established and a protocol has been arranged for orthodontic patients to receive MR scans, future MR studies may be undertaken with relative ease at much lower cost.

Soft tissue influences on growth and development of the dentition and other facial structures are very important to the discipline of orthodontics. Future studies using MR data can be invaluable to moving the profession of orthodontics forward in what is becoming an increasingly soft-tissue focused field. At the current time a graduate student in the LLUSD department of Orthodontics and Dentofacial Orthopedics is continuing the MR research begun in this study.

Additionally, this study has supplemented a group of 12 subjects' beginning orthodontic records including models, photos, traditional radiographs, and CBCT scans with MR scans as well. This database of information that includes the current gold standard of both hard tissue and soft tissue imaging can be immensely valuable for use in future research of all kinds.

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APPENDIX A

PATIENT DEMOGRAPHICS

Patient Identifier	Age	Sex
Patient 1	16 years 0 months	Male
Patient 2	12 years 9 months	Female
Patient 3	12 years 10 months	Male
Patient 4	12 years 2 months	Male
Patient 5	12 years 8 months	Male
Patient 6	28 years 9 months	Female
Patient 7	13 years 6 months	Female
Patient 8	31 years 5 months	Female
Patient 9	12 years 1 month	Male
Patient 10	9 years 11 months	Male
Patient 11	15 years 2 months	Male
Patient 12	13 years 9 months	Female