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Tooth Length Measurements on 3T MR Images: A Retrospective Study

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by

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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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ABBREVIATIONS

CBCT	Cone Beam Computed Tomography
MRI	Magnetic Resonance Imaging
ICC	Intraclass Correlation Coefficient
CI	Confidence Interval
3D-MPR	Three-Demensional Multiplanar Reconstruction
ALARA	As Low As Reasonably Achievable
AAO	American Association of Orthodontics
AAOMR	American Academy of Oral and Maxillofacial Radiology
ADA	American Dental Association

ABSTRACT OF THE THESIS

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Master of Science, Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2015
Dr. V. Leroy Leggitt, Chairperson

Introduction: The purpose of this study was to determine if MRI can be used to accurately measure tooth lengths. **Methods:** MRI tooth length measurements were compared with "actual tooth lengths" as measured on CBCT scans. Twenty three subjects received two scans (one CBCT and one MRI). Tooth length was measured and compared between the resultant images. Intraclass correlations were used for statistical analysis. **Results:** Tooth length measurements made on MRI scans showed moderate to almost perfect agreement with tooth length measurements made on CBCT scans. Higher levels of agreement were present in the maxillary arch compared to the mandibular arch. **Conclusion:** MRI tooth length measurements are similar to CBCT tooth length measurements.

CHAPTER ONE

REVIEW OF LITERATURE

Repetitive maxillo-facial imaging is often used to monitor the progress of orthodontic tooth movement. Currently three dimensional (3-D) imaging is being utilized to improve assessment of the dento-facial structures. This new 3-D technology is particularly helpful in orthodontics to monitor root length[1], bone structure[1], and root angulation.[1,2]

Standard Computed Tomography (CT) has radiation doses that are too high to justify CT use in typical orthodontic situations. Current Cone Beam Computed Tomography (CBCT) machines have smaller radiation doses making CBCT "safer" for most orthodontic needs.[3] It is important to note that CBCT radiation doses are still significantly higher than normal dental radiography. A normal dental FMX series of analog radiographs exposes the patient to about 0.150 microseiverts.[4] Analog panoramic radiographs expose the patient to 54 microseiverts.[5] The effective dose for a single CBCT is 58.9-1025.4 microsieverts.[6] These numbers can be compared with the 3000 microsieverts average annual natural background radiation.[6] The American Dental Association (ADA) recently stated that radiation procedures like CBCT must be used sparingly and only for situations that are deemed necessary for diagnosis.[7] Radiation exposure should be as low as reasonably achievable (ALARA).[7,8]

The ADA released a statement in December 2012 regarding the use the CBCT in dentistry. The statement recommends being careful with patient selection and limiting radiation exposure. In addition dentist should use their professional judgement and weigh the risks and benefits when exposing patients to radiation. The ADA also endorses the ALARA principle when prescribing dental x-rays.[9]

Additionally a joint statement was released by the American Association of Orthodontists (AAO) and the American Academy of Oral and Maxillofacial Radiology (AAOMR) regarding the use of CBCT in orthodontics. The statement says radiographic imaging should be based on the findings of a clinical exam.[10] The benefits of the radiation exposure must always outweigh the risks. CBCT should not be considered routine but a supplement to two-dimensional (2-D) radiographic imaging.[10]

Another form of 3-D imaging available to medical professionals is Magnetic Resonance Imaging (MRI). In contrast to CBCT, MRI uses non-ionizing electromagnetic radiation.[11] MRI allows for repetitive 3-D imaging of dental structures without potential harmful radiation exposure.[12] MRI should be considered first choice for pre-procedural imaging assessment for implant placement.[13]

MRI is now the gold standard for temporomandibular joint (TMJ) imaging because it is used to see the soft tissue component of the joint. Advantages to MRI are: 1) ability to image the TMJ and disk, 2) display of soft and hard tissues, 3) safe to use for patients who are allergic to the contrast agent, 4) all images can be obtained without repositioning of the patient, and 5) the ability to see inflammatory processes.[3] Some disadvantages to MRI include: 1) cost of equipment and cost to patients,[3] 2) accessibility and availability in medical and dental centers,[3] 3) increased possibility of motion artifact due to the length of time to obtain an image,[3] 4) hard tissues not recorded as well,[3] 5) discomfort of claustrophobic patients being confined to a small space,[3] and 6) possible increased incidence of amalgam micro leakage.[14] Another issue is the artifact caused by stainless steel and other metal orthodontic appliances making MRI a problem for patients who are undergoing orthodontic treatments.[3] MRI procedural protocol provides an additional disadvantage because all patients should be screened for the presence of metal objects that may become dangerous projectiles when in proximity to the electromagnetic field.[15]

MRI works by recording a resonance signal from the excited hydrogen atoms created by a magnetic field. The scanner is a magnetic field surrounding the patient and gradient coils are turned on and off to vary the magnetic field. As the magnetic field excites atoms and they return to an equilibrium state energy is sensed. The energy from radio waves and the magnetic field is converted to a number which is processed by a computer and then converted to an image. MRI images the water in the tissues. Different tissues with different water content will display differently on the image. [3]

A recent study concluded that MRI and CBCT images showed similar linear measurements.[16] CBCT was shown to be more accurate than periapical radiographs for measuring tooth lengths.[17] Additionally, CBCT measurements are not significantly different from actual tooth length measurments.[17] Other studies have confirmed the ability of CBCT to accurately measure distance[18] and linear measurements.[19]

The location of impacted teeth is important in orthodontic treatment planning. A prospective study evaluated the diagnosis of impacted teeth using MRI. Impacted teeth were clearly distinguishable from surrounding tissues. In addition, the position and angulation of impacted teeth could be determined in three dimensions. The study achieved accurate analysis of full volumetric morphology of impacted teeth without exposure to ionizing radiation.[20] Another study used MRI to locate impacted teeth.[21] All impacted teeth were located except one tooth in one patient. This study indicates MRI gives us valuable information without the need for ionizing radiation. "MRI is a safe, well-tolerated imaging method which can be used for three-dimensional localization of impacted teeth in both adults and children."[21]

A study looked at improving the contrast of the teeth and jaw during MRI scans. This study described teeth as being "MR-invisible." However, by surrounding the teeth with an "MR-visible" medium the tooth crowns were able to be viewed indirectly.[22] A recent study was conducted to determine if UTE-MRI could be used to image extracted premolar teeth. Linear tooth measurements from the MRI scan were statistically and clinically accurate. Different tooth tissues could be delineated on the MRI scans.[23]

CHAPTER TWO

TOOTH LENGTH MEASUREMENTS ON 3T MR IMAGES: A RETROSPECTIVE STUDY

Abstract

Introduction: The purpose of this study was to determine if MRI can be used to accurately measure tooth lengths. **Methods:** MRI tooth length measurements were compared with "actual tooth lengths" as measured on CBCT scans. Twenty three subjects received two scans (one CBCT and one MRI). Tooth length was measured and compared between the resultant images. Intraclass correlations were used for statistical analysis. **Results:** Tooth length measurements made on MRI scans showed moderate to almost perfect agreement with tooth length measurements made on CBCT scans. Higher levels of agreement were present in the maxillary arch compared to the mandibular arch. **Conclusion:** MRI tooth length measurements are similar to CBCT tooth length measurements.

Introduction

The use of repetitive maxillofacial imaging to monitor the progress of orthodontic treatment is essential to effectively treat orthodontic patients. Three dimensional imaging is rapidly replacing traditional radiographic methods. This new technology is particularly helpful with orthodontic concerns such as root length, bone structure, and root angulation.[1]

The effective dose for a whole head CBCT is 58.9-1025.4 microsieverts. A single scan may expose a patient up to 1/3 of their yearly radiation exposure (estimated at 3000 microsieverts per year).[6] This concern about the radiation exposure was echoed by a recent American Dental Association (ADA) press release stating that radiation procedures like CBCT must be used sparingly and only for situations that are deemed necessary for diagnosis. Radiation exposure to patients should be kept as low as reasonably achievable (ALARA).[7,12]

A joint statement was released by the American Association of Orthodontists (AAO) and the American Academy of Oral and Maxillofacial Radiology (AAOMR) regarding the use of CBCT in orthodontics. The main conclusion of the report was that the benefits to the patient of each exposure must outweigh the risks.[10]

In contrast to CBCT imaging, MRI uses non-ionizing electromagnetic radiation that has few known hazards.[11] MRI allows for repetitive 3-D imaging of dental structures in any age group without worrying about potential harmful radiation exposure.[20]

Advantages to MRI include: 1) imaging of the temporomandibular joint and disk, 2) display of soft and hard tissues, 3) safe use in patients with allergies to contrast agent, 4) elimination of the need to reposition the patient, and 5) the ability to see inflammatory processes. Disadvantages to the use of MRI include: 1) cost of the equipment and cost to patients, 2) access and availability in medical and dental centers, 3) increased possibility of motion artifact because of the length of time to obtain an image, 4) hard tissues not recorded as well, 5) some claustrophobic patients may require sedation, and 6) artifact may be caused by stainless steel and some other metal orthodontic appliances.[3]

Various studies have found other advantages to MRI. MRI images showed accurate linear measurements.[16] Another study has shown that MR images can be used to distinguish impacted teeth from the surrounding tissues and to determine position and angulation of impacted teeth.[20,21]

Materials and Methods

Twenty three non-growing subjects received one whole head NewTom 5G CBCT and one 3T MR scan. MR scans were completed within 3 months of the CBCT scan. Exclusion criteria were the presence of: 1) metal dental restorations, 2) dental implants, 3) stainless steel fixed orthodontic appliances, 4) metal fixed orthodontic retainers, 5) pacemakers, 6) cochlear implants, 7) metal foreign bodies in the eyes, 8) aneurysmal clips, 9) prosthetic metal implants, and 10) pregnancy.

The CBCT scan (NewTom 5G, AFP Imaging, Elmsford, New York, USA) was taken on each patient with a 12x12 - cm x cm field of view (FOV) and a total exposure time of 5.4 seconds. Voxel size was 0.444 mm. Patients were exposed to approximately 66.62 microsieverts of ionizing radiation. Images were obtained with the patient lying in a supine position. Axial slices 0.5 mm thick were created and exported in DICOM format.

The MR scans (TIM/Trio, Siemens Medical Solutions, Erlangen, Germany) were performed using a 3.0T MR imaging system in a 12 channel head array coil. A T1-weighted 3D imaging sequence (Magnetization Prepared Rapid Acquisition by Gradient Echo (MP-RAGE), TR/TE = 1950/2.26 ms) was used to produce contiguous sagittal images of the entire head with an isotropic voxel size of 1.0x1.0x1.0 mm. The scans were exported in DICOM format.

Data Collection

Tooth length was measured on 24 teeth (first molar to first molar in maxillary and mandibular arches) (Appendix A). DICOM data sets were imported into Osirix (v.5.6.). They were oriented by paralleling the occlusal plane to the lower edge of the computer monitor. Tooth length was measured from incisal edge or cusp tip to root apex. Premolars were measured from buccal cusp tip to the root apex of the most buccal root (if multi-rooted). Maxillary molars were measured using the mesio-buccal cusp tip and the mesio-buccal root apex. Mandibular molars were measured using the mesio-buccal cusp tip and the mesial root apex.

The most incisal/occlusal point of an incisal-edge/cusp-tip was located, a point was placed and propagated throughout the entire volume in order to maintain its location while searching for the root apices. The most apical point of the root apex was located and the linear distance between the propagated incisal edge line and the root apex was measured as close to the long axis of the tooth as possible (Fig 1). Tooth length is an apparent tooth length because measurements do not account for both angulation and inclination.

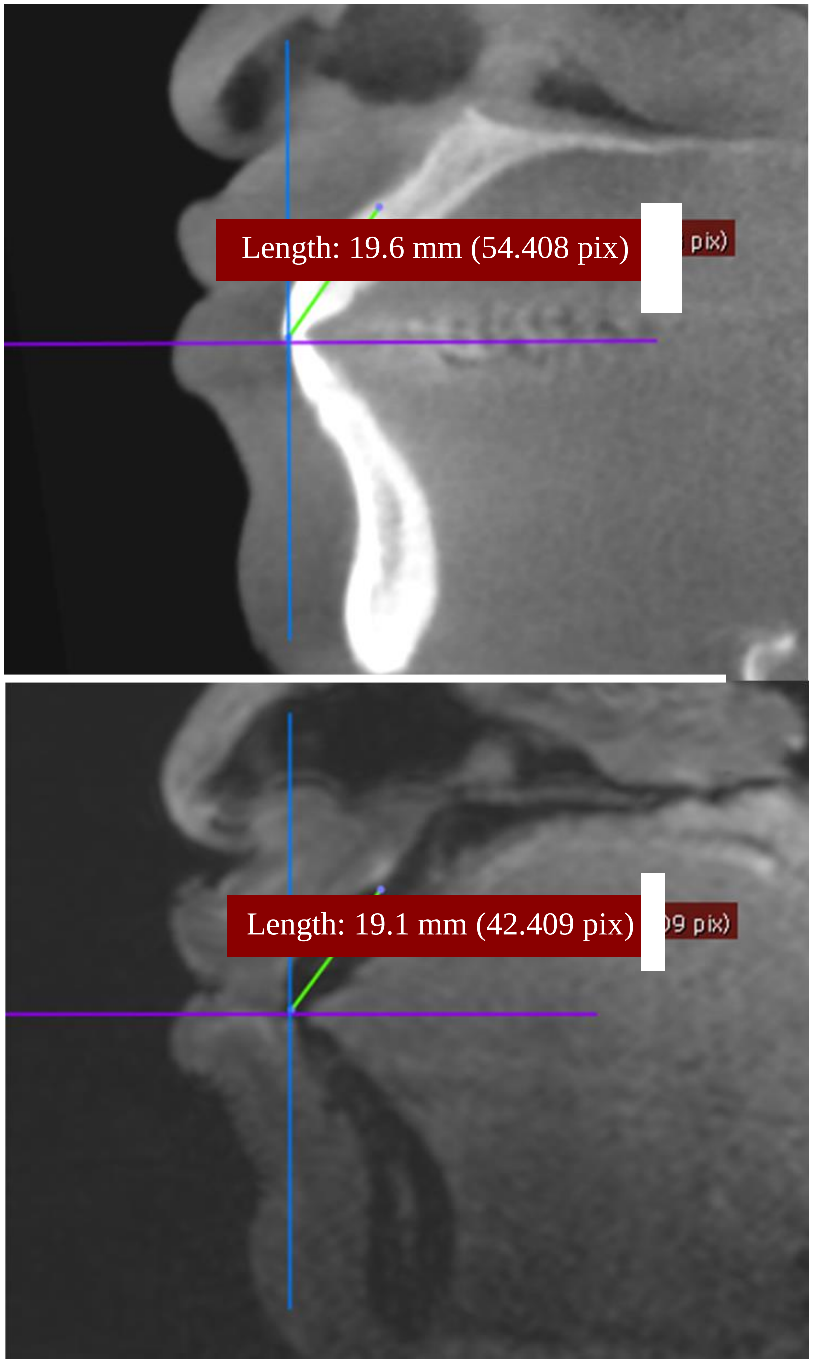

Fig 1. Tooth length measurement methods: (A) CBCT, (B) MRI. Green lines represent apparent tooth length, blue lines represent location of propagated point in the frontal plane, and purple lines represent location of propagated point in the axial plane.

All measurements were performed by one examiner. Linear measurements were made to the nearest 0.01 mm. Reproducibility and intra-rater reliability measurements on three randomly selected patients were made two weeks after the original measurements were taken (Appendix B).

Statistical Analysis

The individual tooth measurements were grouped according to sextant (maxillary right posterior, maxillary anterior, maxillary left posterior, mandibular right posterior, mandibular anterior and mandibular left posterior). The measurements for each arch sextant were compared using intraclass correlation coefficients. Individual tooth length measurements were compared using intraclass correlation coefficients.

When evaluating intraclass correlation coefficients a value of 1 indicates perfect agreement. Values between 0.81 to 0.99 are indicative of almost perfect agreement. Values ranging from 0.61-0.80 show substantial/strong agreement. Values ranging from 0.41-0.60 show moderate agreement. Fair agreement is present between values of 0.21-0.40. Values between 0.01-0.20 indicate a slight agreement. Values of less than 0.01 are interpreted as poor agreement (Table 1).[24]

Table 1. Level of agreement for ICC.[24]

Intraclass Correlation Coefficient (ICC)	Level of Agreement
0.81 - 1.00	Almost Perfect
0.61 - 0.80	Substantial
0.41 - 0.60	Moderate
0.21 - 0.40	Fair
0.01 - 0.20	Slight
0.01	Poor

Results

Arch Sextants

Intraclass correlation coefficients (ICC) showed almost perfect agreement in the maxillary: right posterior (ICC = 0.864; 95% CI = 0.789, 0.913), anterior (ICC = 0.815; 95% CI = 0.734, 0.871) and left posterior sextants (ICC = 0.858; 95% CI = 0.768, 0.913) (Table 1). The ICC values for the mandibular arch showed similar levels of agreement in the various sextants. The mandibular right posterior had almost perfect agreement (ICC = 0.859; 95% CI = 0.439, 0.945), mandibular anterior had moderate agreement (ICC = 0.499; 95% CI = 0.013, 0.739), and the mandibular left posterior sextant had substantial agreement (ICC = 0.771 95% CI = 0.197, 0.911) (Table 2).

The mean measurement difference for the maxillary right posterior sextant was 0.36 ± 2.4 mm; P = 0.06. The mean measurement difference for the maxillary anterior sextant was 0.68 ± 2.1 mm; P = 0.01. The average measurement difference for the maxillary left posterior sextant was 0.80 ± 2.3 mm; P = 0.2 (Table 3). These values in the maxillary arch showed differences in measurement, between MRI and CBCT, of less than a millimeter (Fig 2). The average measurement difference for the mandibular right posterior sextant was 1.77 ± 1.9 mm; P = 0.2. The average measurement difference for the mandibular anterior sextant was 2.49 ± 2.5 mm; P = 0.01. The average measurement difference for the mandibular left posterior sextant was 1.88 ± 1.9 mm; P = 0.2 (Table 3). These values in the mandibular arch showed the differences in measurements to be 1.77 mm to 2.49 mm (Fig 2).

Table 2. Intraclass correlation coefficients for arch sextants.

	Arch Sextant	Intraclass Correlation	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Level of Agreement
Maxillary	Right Posterior	0.864	0.789	0.913	Almost Perfect
	Anterior	0.815	0.734	0.871	Almost Perfect
	Left Posterior	0.858	0.768	0.913	Almost Perfect
Mandibular	Right Posterior	0.859	0.439	0.945	Almost Perfect
	Anterior	0.499	0.013	0.739	Moderate
	Left Posterior	0.771	0.197	0.911	Substantial

Table 3. Mean measurement difference values for arch sextants.

Arch	Arch Sextant	Delta (MRI-CBCT) [mm]	S. D. (±) [mm]	P Value
Maxillary	Right Posterior	0.36	2.41	0.06
	Anterior	0.68	2.09	0.01*
	Left Posterior	0.80	2.34	0.2
Mandibular	Right Posterior	1.88	1.93	0.2
	Anterior	2.49	2.52	0.01*
	Left Posterior	1.77	1.86	0.2

* Statistically significant difference at $\alpha = 0.05$

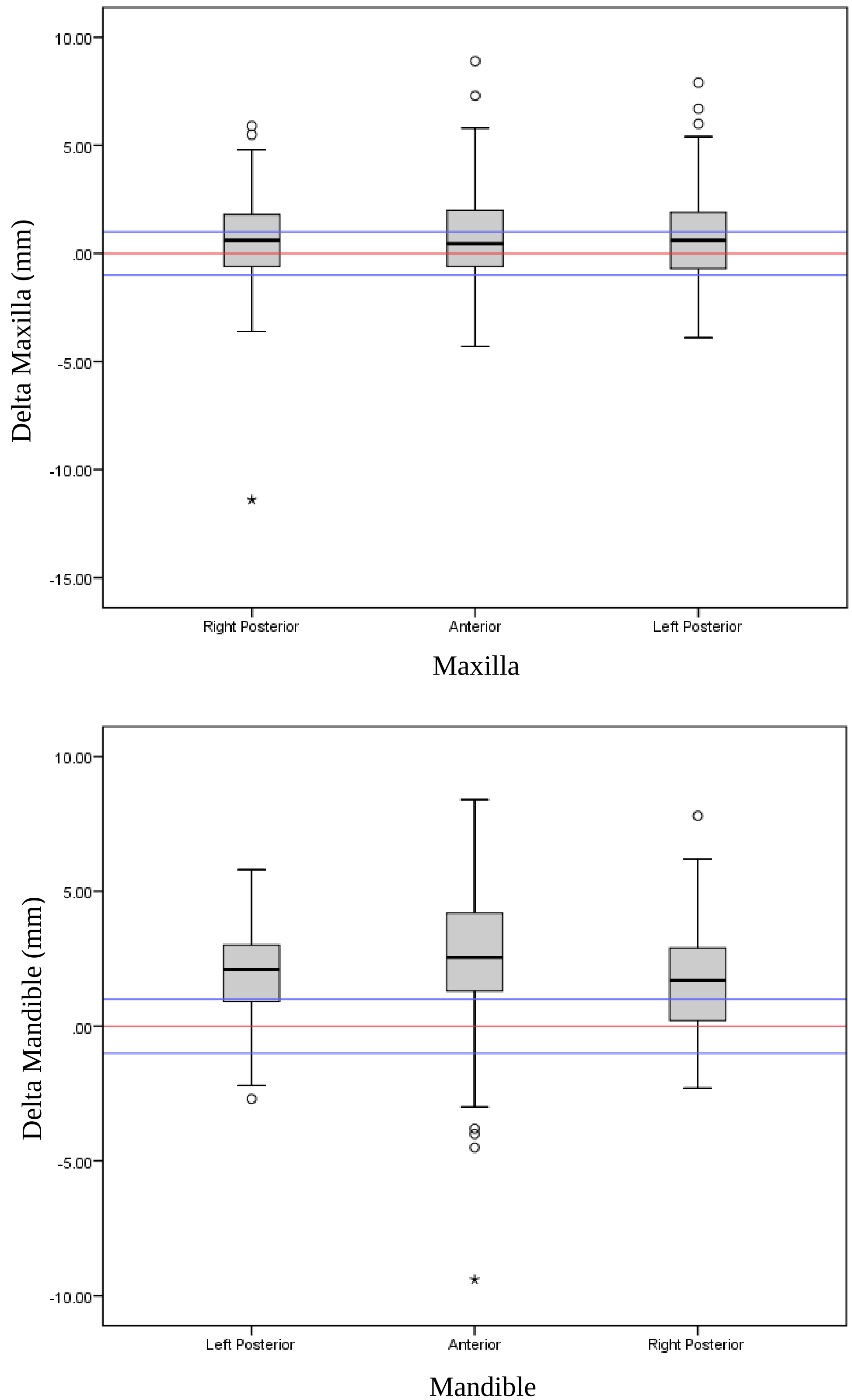

Fig 2. Box plot of delta values (tooth length differences) for arch sextants. Red line is where delta = 0 mm, and blue lines represent a delta of (±) 1 mm.

Individual Teeth

Table 4 shows the intraclass correlation coefficients for all maxillary teeth measured (tooth #'s 3-14) and mandibular teeth measured (tooth #'s 19-30). In the maxillary arch the highest degree of agreement was seen on maxillary second premolars. Tooth #4 demonstrated almost perfect agreement (ICC = 0.960; 95% CI = 0.910, 0.983) and tooth #13 demonstrated almost perfect agreement (ICC = 0.961; 95% CI = 0.911, 0.983) (Table 4). The lowest degree of agreement was on maxillary first premolars, tooth #5 demonstrated moderate agreement (ICC = 0.575; 95% CI = 0.215, 0.796) and tooth #12 demonstrated moderate agreement (ICC = 0.504; 95% CI = 0.118, 0.756) (Table 4).

In the mandibular arch the highest degree of agreement could be seen on mandibular second premolars. Tooth #20 demonstrated almost perfect agreement (ICC = 0.911; 95% CI = 0.772, 0.963) and tooth #29 demonstrated almost perfect agreement (ICC = 0.947; 95% CI = 0.649, 0.984) (Table 4). The lowest degree of agreement was on mandibular central incisors. Tooth #24 demonstrated fair agreement (ICC = 0.202; 95% CI = -0.107, 0.520) and tooth #25 demonstrated slight agreement (ICC = 0.192; 95% CI = -0.107, 0.509) (Table 4).

Table 4. Intraclass correlation coefficients for individual teeth.

	Tooth #	Intraclass Correlation	95% Confidence Interval		Level of Agreement
			Lower Bound	Upper Bound	
Maxillary	3	0.644	0.317	0.833	Substantial
	4	0.960	0.910	0.983	Almost Perfect
	5	0.575	0.215	0.796	Moderate
	6	0.792	0.576	0.906	Substantial
	7	0.855	0.690	0.936	Almost Perfect
	8	0.817	0.357	0.936	Almost Perfect
	9	0.637	0.175	0.847	Substantial
	10	0.848	0.678	0.933	Almost Perfect
	11	0.724	0.426	0.876	Substantial
	12	0.504	0.118	0.756	Moderate
	13	0.961	0.911	0.983	Almost Perfect
	14	0.577	0.078	0.819	Moderate
Mandibular	19	0.640	-0.077	0.884	Substantial
	20	0.911	0.772	0.963	Almost Perfect
	21	0.396	-0.108	0.741	Fair
	22	0.360	-0.056	0.673	Fair
	23	0.437	-0.099	0.763	Moderate
	24	0.202	-0.107	0.520	Fair
	25	0.192	-0.107	0.509	Slight
	26	0.532	0.148	0.773	Moderate
	27	0.505	-0.100	0.824	Moderate
	28	0.428	-0.046	0.732	Moderate
	29	0.947	0.649	0.984	Almost Perfect
	30	0.601	0.106	0.832	Substantial

Reliability

When measurements were repeated on three patients, there was almost perfect agreement for CBCT measurements (ICC = 0.824; 95% CI = 0.733, 0.886). Repeated MRI measurements showed substantial agreement (ICC = 0.605; 95% CI = 0.435, 0.734). Repeated maxillary CBCT measurements showed almost perfect agreement (ICC = 0.868; 95% CI = 0.757, 0.930). Repeated maxillary MRI measurements showed substantial agreement (ICC = 0.653; 95% CI = 0.416, 0.807). Repeated mandibular CBCT measurements showed substantial agreement (ICC = 0.736; 95% CI = 0.512, 0.861). Repeated mandibular MRI measurements showed moderate agreement (ICC = 0.521; 95% CI = 0.227, 0.726) (Table 5).

Repeated CBCT measurements on maxillary sextants showed substantial or almost perfect agreement. Findings demonstrated: maxillary right posterior, substantial agreement (ICC = 0.760; 95% CI = 0.246, 0.940); maxillary anterior, almost perfect agreement (ICC = 0.873; 95% CI = 0.691, 0.951); maxillary left posterior, almost perfect agreement (ICC = 0.900; 95% CI = 0.622, 0.976) (Table 5).

Repeated MRI measurements on maxillary sextants showed moderate or almost perfect agreement. Findings demonstrated: maxillary right posterior showed almost perfect agreement (ICC = 0.833; 95% CI = 0.349, 0.962); maxillary anterior showed moderate agreement (ICC = 0.472; 95% CI = 0.011, 0.765); maxillary left posterior showed almost perfect agreement (ICC = 0.868; 95% CI = 0.548, 0.968) (Table 5).

Repeated CBCT measurements on mandibular sextants showed substantial or almost perfect agreement. Findings demonstrated: mandibular right posterior, substantial agreement (ICC = 0.721; 95% CI = 0.212, 0.928); mandibular anterior, substantial agreement (ICC = 0.765; 95% CI = 0.464, 0.906); mandibular left posterior, substantial agreement (ICC = 0.747; 95% CI = 0.262, 0.935) (Table 5).

Table 5. Intraclass correlation coefficients demonstrating intra-rater reliability.

	Group	Scan	Intraclass Correlation	95% Confidence Interval Lower Bound	Upper Bound	Level of Agreement
	Overall	CBCT	0.824	0.733	0.886	Almost Perfect
		MRI	0.605	0.435	0.734	Substantial
	Maxilla	CBCT	0.868	0.757	0.930	Almost Perfect
		MRI	0.653	0.416	0.807	Substantial
	Mandible	CBCT	0.736	0.512	0.861	Substantial
		MRI	0.521	0.227	0.726	Moderate
Maxilla	Right Posterior	CBCT	0.760	0.246	0.940	Substantial
		MRI	0.883	0.349	0.962	Almost Perfect
	Anterior	CBCT	0.873	0.691	0.951	Almost Perfect
		MRI	0.472	0.011	0.765	Moderate
	Left Posterior	CBCT	0.900	0.622	0.976	Almost Perfect
		MRI	0.868	0.548	0.968	Almost Perfect
Mandible	Right Posterior	CBCT	0.721	0.212	0.928	Substantial
		MRI	0.431	-0.027	0.835	Moderate
	Anterior	CBCT	0.765	0.464	0.906	Substantial
		MRI	0.680	0.211	0.878	Substantial
	Left Posterior	CBCT	0.747	0.262	0.935	Substantial
		MRI	0.425	-0.021	0.827	Moderate

Repeated MRI measurements on mandibular sextants showed substantial or almost perfect agreement. Findings demonstrated: mandibular right posterior, substantial agreement (ICC = 0.431; 95% CI = -0.027, 0.835); mandibular anterior, substantial agreement (ICC = 0.680; 95% CI = 0.211, 0.878); mandibular left posterior, moderate agreement (ICC = 0.425; 95% CI = -0.021, 0.827) (Table 5).

Mean measurement differences for original CBCT (oCBCT) measurements and repeated CBCT (rCBCT) were compared for whole mouth (1.38 ± 1.51 mm), maxillary arch (1.28 ± 1.65 mm), and mandibular arch (1.47 ± 1.37 mm) (Table 6).

Table 6. Mean measurement (absolute value) differences $CBCT^o$ and $CBCT^r$.

Group	Mean Delta (rCBCT-oCBCT) [mm]	SD (±) [mm]
Overall	1.38	1.51
Maxilla	1.28	1.65
Mandible	1.47	1.37

Discussion

This study was designed to explore the use of MRI in orthodontics for the purpose of initial screening, treatment planning, and diagnosis. Tooth length is an important factor in initial diagnosis and treatment planning. MRI completely eliminates the patient's exposure to ionizing radiation. This coincides with the position statements by the ADA and AAO that recommend keeping doses of ionizing radiations down to a level that is "as low as reasonably achievable." [7,10]

Repeated CBCT measurements were compared with original CBCT measurements yielding a mean delta of 1.38 ± 1.51 mm and ICC of 0.824, demonstrating almost perfect agreement. Repeated CBCT measurements and original CBCT measurements in the maxillary arch revealed a mean delta of 1.28 mm and ICC of 0.868, again demonstrating almost perfect agreement. Repeated mandibular CBCT measurements and original mandibular CBCT measurements had a mean delta of 1.47 mm and ICC of 0.736, demonstrating substantial agreement. Mean differences of up to 1.65 mm[25] to 2 mm[26] have been considered clinically acceptable. This study demonstrates that a delta of 1.38 mm is the best that can be achieved in measuring root lengths using CBCT. This indicates that the clinician can expect that CBCT measurements are only accurate to about 1.5 mm.

Correlation values from this study tell us MRI can be used to accurately see teeth in the maxillary arch. Looking at segments of the maxillary arch there was almost perfect agreement between the MRI and CBCT tooth lengths. Individual teeth showed correlations that were mostly substantial to near perfect. The moderate correlation values in the maxilla were seen on the first premolars and left first molar. These relatively lower correlations on the first premolars may be attributed to the proximity to the maxillary sinus, variations in root morphology and possible dilacerations, or perhaps other adjacent anatomical structures. Additionally, since MRI scans last longer than CBCT scans, motion artifact may have had an effect on accuracy of MRI scans.

ICC values in the mandibular arch were not as good as the maxillary arch and it may be clinically desirable for these values to show greater agreement. Four factors contributed to the less desirable agreements. First, the incisal edges and cusp tips of the mandibular teeth were difficult to pinpoint in MRI scans as they are hidden in the occlusion with the maxillary teeth. Second, the apex of the roots in the mandibular anteriors tended to blend in with the cortical bone in the symphyseal area, again making it difficult to locate an exact point of apex. Third, motion artifact likely contributed some of the lesser correlation, particularly with MRI measurements. Fourth, the reliability error shows that the largest measurement differences were in the mandibular arch. If MRI were to be used for clinical diagnosis it might be advisable to take supplementary PA's of the mandibular anteriors.

Improvements can be made to this study. Tooth measurements were made in a 3D MPR view as opposed to the traditional PA or panoramic images. Perhaps an alternative imaging software would yield more favorable or less favorable results.

One improvement to future studies would be the addition of a contrast medium to the MR scans. A German study used an "MR-visible" medium which improved the visualization of the teeth.[22] The use of a substance such as water or an alginate bite registration could enhance the clinicians ability to see the morphology of the crowns of the teeth.

Orthodontic patients are generally young and more susceptible to the harmful effects of ionizing radiation. We must make every effort to minimize or eliminate the exposure of our patients to ionizing radiation. The ability to use MRI in orthodontic diagnosis and screening could be an important step in the right direction because it would completely eliminate the patients' exposure to ionizing radiation, at least at initial screening and diagnosis. The principle of ALARA would be put to maximum effect.

Conclusions

1. MRI has nearly perfect agreement with CBCT when looking at tooth length measurements in the maxillary arch sextants.
2. MRI has at least moderate agreement with CBCT when looking at individual tooth lengths in the maxillary arch.
3. There is more variability in agreement for tooth length measurements in the mandibular arch.
4. Tooth length measurements are repeatable with both MRI and CBCT.

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CHAPTER THREE

EXPANDED DISCUSSION

An almost perfect level of agreement was found in the maxillary: right posterior, anterior, and left posterior sextant (Table 2). These coefficients demonstrate a near perfect agreement between tooth length measurements made on CBCT (considered the gold standard) and tooth length measurements made on MRI scans. The confidence intervals also tell us that most of the data was grouped within range of strong agreement up to almost perfect agreement. This level of agreement would indicate that MRI measurements made in the maxillary arch are statistically similar to CBCT measurements and can be interchangeable. MRI can be considered clinically equivalent to CBCT in determining tooth length in the maxillary arch.

When looking at the correlation between measurements made on the mandibular arch, a lesser amount of correlation was observed in sextants of the mandibular arch. The right posterior sextant showed almost perfect agreement (Table 2) similar to sextants in the maxillary arch. However, the confidence interval for this sextant is not as good as the maxillary arch but it is still acceptable. The left posterior sextant of the mandibular arch showed a substantial level of agreement, but has a very large confidence interval (Table 2). These measurements can be considered similar enough to be interchangeable. The mandibular anterior sextant shows a moderate level of agreement, which raises clinical concerns as to the similarities between the two measurements. This most likely can be attributed to the difficulty in locating mandibular incisal edges and differentiating cortical bone from root apices on MRI scans. The relatively moderate agreements for mandibular anterior sextant was further explored in the study when individual tooth lengths were measured and compared.

The difference in tooth length measurements help show a better picture. The study did not expect for there to be zero difference between the measurements, because they were being made at different times and with some landmark location error. However, a small difference between the measurements would be clinically acceptable. The measurement differences in the maxillary arch show less than a millimeter of difference between MRI and CBCT (Table 3). These values are clinically useful because they are smaller than the computerized point used to locate the root apices and incisal edges, or cusp tips, which was one millimeter in diameter. Therefore the difference in measurement from CBCT to MRI was less than the diameter of the points being used to make the measurements and could be considered clinically insignificant. Even slight variances in placing these points would account for the measurement differences in the maxillary arch. The values in the mandibular arch show the difference in measurements to be 1.77 mm, or greater, which is more clinically significant (Table 3). A difference of nearly 2 mm can easily be detected by the human eye, therefore this degree of difference is clinically significant and helps to demonstrate the difficulty in locating the actual incisal edges or cusp tips as well as the root apices.

Variations in measurements for individual teeth were evaluated in order to get a better picture or idea of where the two modalities of tooth measurement had the highest and lowest agreements values.

The highest degree of agreement could be seen on maxillary second premolars. This value indicated a near perfect agreement between the MRI and CBCT measurements. The lowest degree of agreement was on maxillary first premolars. However, they still showed moderate agreement. Left first molars also showed moderate agreement. Having moderate agreement, although not ideal, was clinically acceptable because the average difference in tooth length measurements in posterior sextants were still less than a millimeter.

All maxillary anterior teeth from canine to canine showed substantial to almost perfect agreement. Canines showed values indicating substantial or strong agreement. Lateral incisors had correlation coefficients showing near perfect agreement. Central incisors had correlation coefficients demonstrating substantial and near perfect agreement, the left central incisor having the substantial agreement and right central incisor having near perfect agreement (Table 4). With these high levels of correlation, and average difference in measurements being under a millimeter, it is acceptable to say MRI is similar enough to CBCT to be used clinically to determine tooth length when looking at teeth in the anterior maxilla.

The maxillary anterior sextant showed an average tooth length difference of 0.68 mm with data sets which were tested to be significantly different (Table 3). Although this finding was statistically significant the average difference was not deemed to be clinically significant as this small of a difference could realistically be the result of slight variations in measurements or perhaps a systematic error in measuring one imaging modality compared to the other one.

In the mandibular arch the highest degree of agreement could be seen on mandibular second premolars, near perfect agreement between the MRI and CBCT measurements. Additionally, the small confidence interval demonstrates that most of the individual correlation coefficients were in the range of substantial agreement or higher. The lowest degree of agreement was on mandibular central incisors showing only slight to fair agreement. These correlation coefficients, the relatively wide confidence interval, and average difference in tooth length measurements of nearly 2.5 mm suggested these measurements were of much lower clinical acceptance, again possibly the result of difficulties in locating points of interest. First molars both showed substantial agreement. First premolars showed fair to moderate agreement (Table 4). Mandibular posterior teeth had tooth length differences of nearly two millimeters, which is less clinically acceptable than the tooth length differences observed in the maxillary arch (Table 3).

All mandibular anterior teeth from canine to canine, excluding mandibular central incisors which were reported above, showed slight to moderate agreement at most. Canines showed fair and moderate agreement on the left and right respectively. Lateral incisors had correlation coefficients demonstrating moderate agreement on both the left and right respectively (Table 4). Mandibular anterior teeth showed average tooth length differences that were tested to be statistically different, and at 2.49 mm average difference in this sextant the clinical acceptance is lacking.

In general mandibular teeth were difficult to measure as their incisal edges and cusp tips were often obscured by their occluding with the maxillary teeth. This made it difficult to accurately and consistently locate a point to be used for the incisal/occlusal portion of the measurement. Additionally, the mandibular anterior teeth posed a unique problem. Many of the subjects had thin alveolar process on top of a small symphysis. The root apex was often in close proximity to the cortical bone either buccal or lingual making it difficult to locate the apex, possibly resulting in a systematic error in locating the root apices.

When measurements were repeated on three patients, intraclass correlation coefficients showed almost perfect agreement over all for CBCT measurements. This is supported by the almost perfect agreement seen in the repeated CBCT measurements in the maxilla and the substantial agreement seen in repeated CBCT measurements in the mandible. This indicated that location of cusp tips or incisal edges and root apices were consistent and repeatable on the CBCT scans when looking at a complete arch. Repeated MRI measurement showed substantial agreement overall, substantial agreement in the maxilla, and moderate agreement in the mandible (Table 5). Locating cusp tips or incisal edges and root apices on the MRI scans seemed to be less consistent and less repeatable than on CBCT scans when looking at the arch as a whole.

Reliability of measurements made on arch sextants continued to show substantial or almost perfect agreement when measurements were repeated on CBCT scans. Mandibular sextants showed less agreement than maxillary sextants (Table 5). CBCT measurements were reliable and repeatable.

Reliability of measurements made with MRI on arch sextants demonstrated at least moderate agreement in all sextants. Both maxillary posterior sextants showed almost perfect agreement, indicating reliable and repeatable measurements on MRI. Maxillary anterior tooth length measurements showed moderate agreement. Mandibular posterior sextants demonstrated moderate agreement with repeated measurement on MRI scans. This supports what was seen in total arch comparisons, and a possible difficultly in consistently locating cusp tips and root apices (Table 5).

Mandibular anterior sextant repeated MRI measurements demonstrated substantial agreement, an interesting finding, considering mandibular anterior teeth had the lowest levels of correlation, slight to moderate agreement (Table 4 and Table 5), and average differences in tooth length measurements of 2.49 mm. The substantial agreement seen in MRI repeated scans indicates incisal edges and root apices were consistently measured to be in the same places. A possible explanation for this finding would be a systematic error in locating incisal edges, root apices, and/or measuring mandibular anterior tooth length on MRI scans. Further study is needed to explore these findings.

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APPENDIX A

TOOTH LENGTH MEASUREMENTS (MM) ON CBCT AND MRI

		Tooth #																							
		Maxillary Arch												Mandibular Arch											
Subject	**Scan**	3	4	5	6	7	8	9	10	11	12	13	14	19	20	21	22	23	24	25	26	27	28	29	30
1	**CBCT**	19.0	15.5	20.0	21.1	20.2	20.2	21.5	20.9	22.0	19.7	16.0	18.0	20.1	22.0	23.5	24.9	22.8	22.4	23.6	23.7	23.8	20.9	20.2	21.7
	MRI	21.8	21.0	21.1	25.1	20.0	24.1	26.1	21.6	27.8	21.3	18.3	24.7	23.9	20.2	23.7	25.9	22.1	21.9	25.3	25.4	26.6	23.8	22.8	21.2
3	**CBCT**	20.7	23.7	23.9	29.7	24.5	26.8	24.7	25.3	29.3	25.2	25.7	20.7	22.1	24.6	25.2	27.6	25.2	25.8	24.4	23.3	20.7	22.8	24.3	21.7
	MRI	22.6	24.3	23.4	27.6	26.6	29.1	28.1	24.1	29.5	24.0	24.5	20.0	24.9	24.0	25.9	29.9	27.7	26.8	27.2	27.0	25.8	25.9	24.5	21.3
4	**CBCT**	23.5	26.7	25.7	32.5	27.4	28.5	26.2	25.1	29.0	24.4	27.5	24.1	25.9	25.7	23.5	30.8	26.5	23.0	22.6	29.5	25.5	23.9	26.6	24.0
	MRI	25.6	29.7	31.6	35.3	26.6	29.0	30.3	26.4	31.9	29.5	27.7	26.0	25.7	27.0	27.2	32.1	28.3	27.9	27.0	30.0	33.9	30.1	29.3	27.5
6	**CBCT**	17.8	14.6	18.7	22.9	17.4	17.8	19.6	18.6	21.5	17.1	16.5	17.1	19.0	20.8	19.9	20.4	19.7	18.6	21.1	21.7	21.0	22.4	19.5	17.0
	MRI	15.9	16.6	19.4	18.6	17.5	18.6	19.1	17.5	19.0	18.4	19.0	17.7	19.2	18.6	25.7	24.1	22.3	22.5	23.0	23.1	23.2	22.0	19.9	20.0
7	**CBCT**	19.9	21.6	18.3	24.4	19.5	23.8	24.4	19.9	22.4	19.5	19.5	20.5	21.1	22.3	21.4	23.3	23.0	21.2	20.7	21.1	22.9	21.9	22.5	22.5
	MRI	19.4	23.7	17.7	22.6	18.3	24.6	23.8	18.7	21.9	20.1	21.1	20.9	23.7	25.2	23.7	28.6	27.2	17.4	17.7	17.1	24.8	25.9	24.8	21.0
8	**CBCT**	22.7	19.6	21.6	25.7	25.2	23.7	21.6	20.6	27.9	19.9	22.2	22.5	23.6	20.8	22.6	27.4	22.1	19.8	19.4	22.1	26.5	22.2	0.0	23.4
	MRI	23.0	18.0	18.0	27.4	21.5	28.0	24.1	23.8	28.1	19.5	18.3	23.4	26.3	24.9	26.5	29.4	24.4	23.2	26.1	27.0	29.6	20.4	0.0	25.8
9	**CBCT**	21.9	23.7	23.3	27.8	23.2	23.6	23.5	24.1	27.1	18.4	21.4	22.7	23.4	23.2	25.5	27.4	23.6	21.0	20.7	24.1	29.1	25.6	21.9	24.8
	MRI	20.2	22.5	23.6	27.8	22.5	25.2	24.9	22.8	28.4	24.4	21.3	21.6	26.6	26.5	28.3	29.0	25.3	23.4	25.3	26.8	33.3	28.7	24.5	27.4
10	**CBCT**	16.4	16.9	18.5	24.1	19.0	17.9	14.9	19.8	24.5	19.6	19.2	16.1	17.8	18.3	18.8	24.1	20.0	19.5	18.3	20.2	21.9	20.3	17.4	17.9
	MRI	20.0	19.6	19.5	23.9	17.9	17.8	17.7	20.7	25.4	19.4	15.3	19.4	19.0	19.3	20.2	26.5	25.6	26.4	22.9	15.7	24.8	20.3	19.0	20.5
11	**CBCT**	20.4	22.5	23.4	25.1	24.5	25.5	25.7	23.9	25.7	22.3	21.4	21.0	23.7	22.9	21.5	27.3	23.3	26.0	25.6	23.7	26.1	24.7	23.6	23.0
	MRI	22.3	21.2	28.2	26.1	23.2	28.0	27.7	23.7	26.6	21.6	22.2	21.7	24.9	25.2	24.8	28.9	25.1	24.3	24.4	23.7	28.9	25.2	25.9	24.7
12	**CBCT**	21.3	21.0	22.0	28.5	25.7	19.9	23.9	25.1	28.0	22.1	24.4	22.5	21.4	24.2	21.5	22.5	21.2	22.3	22.1	20.8	20.7	23.7	28.8	20.8
	MRI	24.6	21.7	21.0	33.9	25.4	20.0	25.6	25.2	35.3	20.9	25.8	25.8	24.5	25.2	24.1	27.4	22.9	25.3	23.7	21.6	26.2	23.1	36.6	22.0
13	**CBCT**	22.0	25.5	24.1	28.9	24.9	26.0	26.5	24.4	30.0	25.0	25.7	22.2	22.8	26.1	22.7	29.3	25.2	21.3	24.1	23.4	29.1	22.4	25.4	23.8
	MRI	22.9	22.6	24.4	32.5	27.3	26.9	26.4	24.7	29.6	23.5	29.4	27.6	25.3	23.4	28.5	33.4	26.5	24.0	25.7	25.2	30.8	26.7	26.6	25.5
14	**CBCT**	19.8	19.0	18.6	25.4	22.6	20.3	20.5	21.5	20.8	22.4	19.2	17.8	18.4	23.4	20.9	23.2	23.0	23.3	22.9	22.7	23.2	21.6	21.6	20.7
	MRI	19.8	18.7	19.0	25.5	21.0	19.6	22.9	22.4	24.5	19.2	21.3	18.8	23.5	21.4	25.1	29.1	25.1	21.4	22.5	25.9	25.1	22.6	21.3	20.9
15	**CBCT**	19.6	19.2	19.7	21.0	19.7	18.7	19.7	19.2	21.0	19.6	20.3	17.4	19.0	18.0	19.8	22.6	22.7	21.7	21.5	21.6	22.1	18.8	18.5	19.6
	MRI	16.1	17.6	19.5	23.2	18.5	18.4	18.8	19.3	24.2	18.0	20.1	16.7	19.7	20.1	22.0	26.5	24.8	22.8	24.0	22.7	26.9	22.5	20.8	20.4
16	**CBCT**	21.3	21.5	20.3	28.9	20.5	23.0	24.2	21.6	28.3	22.7	22.3	22.0	24.4	24.0	25.4	24.8	23.5	19.6	21.4	21.3	26.0	24.4	21.4	23.1
	MRI	23.1	22.7	21.1	28.6	21.4	27.1	24.8	21.5	30.4	20.4	21.9	23.8	25.7	25.2	27.6	29.4	28.5	25.7	28.0	27.4	30.6	28.8	24.9	25.6
17	**CBCT**	20.5	21.1	20.5	24.2	22.5	21.5	20.0	23.4	23.2	20.2	19.0	19.3	21.9	20.6	24.4	26.0	23.4	22.1	21.5	24.4	25.4	24.2	23.5	22.6
	MRI	22.6	21.6	18.9	24.2	21.0	22.4	22.8	22.8	24.0	20.8	22.6	21.2	23.4	22.3	25.5	32.0	29.9	24.9	27.1	28.8	30.2	25.3	25.1	24.2
18	**CBCT**	24.4	27.2	28.0	29.8	24.7	27.6	27.8	26.7	30.6	25.2	27.6	23.0	25.5	25.3	25.7	29.5	22.4	21.2	22.5	23.9	29.9	24.3	26.4	25.3
	MRI	24.2	26.7	24.9	27.3	24.9	26.6	27.0	24.2	28.1	25.2	26.4	24.3	26.9	24.5	26.6	31.6	20.7	22.6	26.4	24.2	31.2	27.5	26.0	25.5
19	**CBCT**	19.6	17.6	18.7	23.3	17.8	20.5	20.8	19.4	24.2	18.6	18.7	17.7	19.4	18.7	19.8	22.2	17.8	16.9	17.5	20.3	25.3	18.9	18.2	18.5
	MRI	21.4	18.7	20.0	24.1	19.6	23.6	29.7	17.5	24.2	17.9	19.3	17.8	24.0	21.7	23.3	25.4	20.7	23.1	23.1	24.7	24.7	22.6	21.0	24.2
20	**CBCT**	17.1	19.0	22.1	24.4	18.6	22.7	22.5	17.5	22.2	20.0	19.1	17.6	18.4	19.2	20.5	23.9	20.6	18.8	19.4	19.9	22.5	20.8	19.5	18.2
	MRI	18.2	21.1	22.7	25.5	19.8	24.7	25.9	18.0	24.6	19.5	20.5	18.7	18.6	21.5	24.3	24.5	20.6	21.7	20.0	20.9	25.5	21.1	21.2	19.4
21	**CBCT**	18.6	22.0	20.7	26.2	24.3	22.0	20.0	23.3	27.8	22.9	21.7	18.0	21.9	21.9	21.1	22.3	21.3	19.6	20.6	23.4	24.0	20.2	19.8	21.0
	MRI	21.0	20.5	22.3	28.0	24.9	23.1	21.7	25.6	27.5	22.1	20.3	21.3	23.1	25.7	26.3	28.4	26.8	22.5	22.7	24.6	28.1	24.1	22.1	23.4
22	**CBCT**	20.4	0.0	21.0	24.9	20.1	22.7	24.0	22.2	27.1	21.1	0.0	19.7	19.4	0.0	21.7	24.0	21.8	19.2	19.1	20.3	24.4	22.2	0.0	20.8
	MRI	21.3	0.0	9.6	25.8	18.7	24.6	23.7	19.3	27.3	19.1	0.0	18.0	21.8	0.0	20.4	27.7	23.3	24.3	24.6	23.5	26.1	22.4	0.0	21.0
23	**CBCT**	18.7	0.0	19.3	20.3	20.8	20.6	21.0	20.8	21.4	18.4	0.0	17.6	18.7	19.0	21.5	18.9	18.5	18.5	20.1	20.5	18.8	22.7	18.3	19.1
	MRI	16.3	0.0	19.5	21.6	17.4	19.7	20.9	19.6	22.0	26.3	0.0	21.0	20.5	21.8	22.0	23.5	21.1	21.5	23.9	20.9	23.0	21.0	19.1	20.4
24	**CBCT**	19.0	20.6	22.4	24.0	18.8	22.4	22.6	21.0	25.5	21.1	20.2	17.2	20.2	20.9	21.8	25.8	21.3	20.3	21.5	23.3	24.6	20.4	20.7	20.1
	MRI	20.7	18.8	20.8	22.1	18.3	22.8	24.6	20.5	26.8	20.9	20.9	21.5	21.1	23.0	24.4	27.9	24.9	20.5	21.6	23.2	25.9	24.1	23.0	24.6
26	**CBCT**	21.0	23.0	22.3	26.7	23.8	22.5	26.3	23.5	26.2	19.4	22.2	19.7	21.2	23.7	24.9	29.0	23.0	22.7	23.1	24.7	26.4	23.9	24.5	23.4
	MRI	22.0	23.7	23.1	26.4	21.3	25.0	25.4	22.9	24.9	17.6	23.6	22.6	22.4	22.7	27.8	19.6	25.6	25.3	23.4	23.9	27.8	26.7	24.0	21.1

APPENDIX B

REPEATED TOOTH LENGTH MEASUREMENTS (MM) ON CBCT AND MRI

		Tooth #																							
		Maxillary Arch												Mandibular Arch											
Subject	**Scan**	3	4	5	6	7	8	9	10	11	12	13	14	19	20	21	22	23	24	25	26	27	28	29	30
6	**CBCT**	18.2	19.6	20.3	24.0	17.6	17.3	19.2	18.7	18.2	19.9	19.5	17.7	17.6	20.9	18.9	20.8	18.8	17.9	19.3	19.0	19.8	17.3	19.0	17.8
	MRI	16.0	17.5	19.4	24.5	18.9	21.6	20.0	23.6	21.6	19.2	18.8	19.5	20.4	19.9	21.2	22.5	21.8	22.5	23.6	23.5	22.5	20.1	21.5	20.6
12	**CBCT**	24.0	21.1	23.7	27.6	24.2	20.6	23.6	24.0	28.8	22.0	24.0	21.7	21.1	22.8	22.5	25.0	20.9	22.1	21.6	19.0	24.2	24.0	23.6	19.6
	MRI	24.2	22.7	24.7	25.8	26.2	24.5	24.4	24.7	26.4	21.6	23.9	23.0	22.1	21.9	23.1	23.2	22.9	23.0	22.2	21.2	23.7	23.9	24.4	23.4
13	**CBCT**	21.5	25.3	23.9	37.5	24.1	26.4	25.7	22.8	30.8	26.0	26.6	21.9	23.5	22.4	23.4	25.8	23.6	21.2	21.1	22.8	26.7	22.7	26.8	23.9
	MRI	21.2	23.4	23.3	24.3	23.6	25.1	25.0	26.8	27.1	25.1	26.9	24.9	24.6	26.9	23.5	28.1	25.6	24.7	24.4	25.5	27.0	25.0	27.4	25.1