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LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
Faculty of Graduate Studies

Comparison of Tooth Length Measurements Made on CBCT and 3T MR Images

by

Danielle A. Piano

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

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September 2017

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

, Chairperson

V. Leroy Leggitt, Professor of Orthodontics and Dentofacial Orthopedics

Joseph Caruso, Professor of Orthodontics and Dentofacial Orthopedics

James R. Farrage, Associate Professor of Orthodontics and Dentofacial Orthopedics

Roland Neufeld, Associate Professor Orthodontics and Dentofacial Orthopedics

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To my family and friends, you have always been a source of inspiration, unconditional love and guidance. Your support throughout the decades of academics leading up to this finish line has meant everything to me, and I love you all so much.

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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
ICRP	International Commission of Radiological Protection
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 THESIS

Comparison of Tooth Length Measurements Made on CBCT and 3T MR Images

by

Danielle A. Piano

Master of Science, Graduate Program in Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2017
Dr. V. Leroy Leggitt, Chairperson

Objective: The aim of this study is to compare tooth length measurements made on cone beam computed tomography (CBCT) scans and 3-Tesla (3T) magnetic resonance (MR) scans.

Materials and Methods: One CBCT scan (NewTom5G, AFP Imaging, USA) and one 3T MR scan (Siemens Medical Solutions, DE) as performed on 12 subjects. CBCT images were captured with an 18x16 inch field of view that covered the whole head. Contiguous sagittal MR images of the whole head were produced in a 3.0T imaging system with a T1-weighted 3D imaging sequence (Magnetization Prepared Rapid Acquisition by Gradient Echo (MP-RAGE), TP/TE = 1950/2.26 ms) and isotropic resolution of 1.0x1.0x1.0 mm. DICOM formatted images from each scan were oriented in all three planes of space and 4 mm thick slices were made through the long axis of all permanent teeth. Tooth length measurements were determined from the slices (336 tooth length measurements) using Invivo (v5.4) imaging software (Anatomage Inc., San Jose, CA).

Results: Overall data showed good correlation with Intraclass Correlation Coefficient of 0.981 ($P<0.001$) and Pearson's Correlation of 0.981 ($P<0.001$). The mean difference between the collective measurements was 0.04 mm ± 0.77 mm. Measurements in the maxilla (ICC 0.982) had slightly higher correlation than those in the mandible (0.980). Second premolars were found to have the highest correlation of all tooth types (ICC 0.984, $P<0.001$).

Conclusions: Measurements made of 3T MR images have good correlation with equivalent CBCT measurements. Larger sample size is required to evaluate differences found in data. Future studies are required to evaluate MRI as a diagnostic imaging modality in the field of orthodontics.

CHAPTER ONE

EXTENDED LITERATURE REVIEW

Imaging plays an essential role throughout the treatment of an orthodontic patient. There are multiple time points in which images are required including: prior to initiating treatment to improve treatment planning, during treatment to assess progress, and at the completion of treatment to assess final outcome. Orthodontic and dentofacial orthopedic diagnosis and treatment planning has relied on two-dimensional (2D) planar radiographic imaging and cephalometry for nearly a century.[1] Traditionally these images have included lateral cephalograms, panoramic radiographs, and full mouth surveys consisting of multiple periapical and bitewing radiographs. These radiographs provide practitioners with necessary information concerning the facial hard and soft tissues and the dentition to make decisions regarding treatment modalities. 2D imaging techniques present several disadvantages, with the most significant being the reduction of a three-dimensional (3D) object to a two-dimensional view. The result is tissue overlapping, landmark obstruction, distortion, magnification and object displacement.[2-5] Recognizing the importance of comprehensive visualization of craniofacial structures in orthodontics initiated the trend towards 3D imaging technologies.[2,6-8]

Cone beam computed tomography was introduced to the dental field over two decades ago and has become the most widely used form of 3D imaging technology in orthodontics today.[6] CBCT technology demonstrates superior image fidelity and provides views of hard and soft tissue structures unobtainable with conventional radiographs.[6] Thus, allowing the orthodontist to overcome previous challenges involved with extrapolating 3D information from a 2D image, especially in cases involving impacted teeth, airway, temporomandibular joint disorders, asymmetries, and other craniofacial complexities.[6,8,9] Consequently, supporting CBCT as an excellent tool for accurate diagnosis, more predictable treatment planning, more efficient patient management and education, improved treatment outcome and patient satisfaction.[6] Advances have also been made to reduce the effective dose of ionizing radiation associated with the imaging technique – including automatic exposure control, sampling, and pulsed exposure.[10] While there is no argument against the usefulness of these images in diagnosis and treatment planning, patients undergoing CBCT scans are being exposed to ionizing radiation.[1,7,11,12] Long-term stochastic effects of ionizing radiation include increased risk of radiation-induced carcinogenesis, particularly in children.[1] Heightened radio-sensitivity is observed in growing children, making it crucial for clinicians to minimize radiation exposure.

In effort to decrease exposure, health professionals have adopted the "As Low As Reasonably Achievable" (ALARA) principle.[11] This requires a risk/benefit joint analysis to be completed, and the clinician to make their imaging plan based on that analysis. Radiographic images providing benefits that outweigh the risks of radiation exposure are deemed acceptable by the health professions.[8,13] In a systematic review of the literature by De Vos et al., significant inconsistencies and discrepancies were found in the reporting of CBCT device settings, properties, and radiation dose between papers. They also reported inconsistencies in how studies reported the CBCT acquisition protocol, which is significant since device settings, image quality, and the resulting radiation dose are dependent on one another. This study concluded that there is a lack of evidence-based data on the radiation dose for CBCT imaging.[8] Brooks et al., performed a study that compared CBCT scan and conventional radiography commonly used in orthodontics. Their data found the effective radiation dose for a panoramic radiograph ranged from 5.5 to 22.0 microsieverts and a lateral cephalogram from 2.2 to 3.4 microsieverts. In comparison, a CBCT scan ranged from 58.9 to 1025.4 microsieverts.[12] Another study measured the effective dose during CBCT scans to range between 68 to 1073 microsieverts.[14] Further research regarding patient outcomes is needed to determine if, and when, the use of CBCT scans justifiably exposes orthodontic patients to increased radiation.[8,13,14] Nevertheless, there is no safe threshold and any exposure can lead to cancer-causing effects. In accordance with the ALARA principle, it is reasonable to explore a radiation-free imaging technique.

Magnetic resonance imaging (MRI) is a technology that yields 3D imaging of the head and neck area without exposing patients to ionizing radiation, and is the highest contrast resolution medical imaging technique.[2] MRI is commonly used in the medical field to diagnose various pathologies and conditions, and has often been employed by dental professionals to investigate temporomandibular joints, nerves, and soft tissue pathologies such as tumors.[15] MR images provide visualization of both hard and soft tissue structures, and allow the provider to distinguish between adjacent soft tissues. Images are obtained with radiofrequency (RF) radiation in the presence of carefully controlled magnetic fields.[16] The machine achieves a resonance signal from hydrogen nuclei (protons) in water and fat.[2,16] RF pulses stimulate hydrogen atoms, which emit energy that is converted to numbers. These numbers are processed on a computer and converted to an image. Essentially, MRI is imaging water molecules in the tissue.[2,16] The differential densities of protons and the molecular environment influence the relative intensities of the MR signal generated, producing distinction between various tissues. MR imaging sequences can be divided into two groups: T1- or T2-weighted. T1-weighted have a longitudinal proton relation time, and T2-weighted have a transverse proton relation time.[15] The contrast between the two types enables the T1-weighted image to depict normal anatomy, while T2-weighted images are used to detect infection, hemorrhage, and tumors.[15]

Although certain instances of pathology, such as the presence of oral cancer, require T2-weighted images, typical orthodontic diagnosis can be completed using T1-weighted images. In T1-weighted images, the external cortical plate appears black, which differs from the radiopaque appearance observed on traditional radiographs.[15] The MRI appearance is due to an absence of water or protons in cortical bone, which produces a low signal during MR imaging. Conversely, high concentrations of protons create a strong signal and appear very bright in T1-weighted images, as seen with the fatty bone marrow of cancellous bone. Nerves are identified on MR images by distinguishing between the distinct dark neurovascular channels within the bright cancellous bone. Understanding how to identify these tissues enables the provider to view and measure the jaw bones. Soft tissues are easily detected on MR images because of their high density of hydrogen atoms, and appear as a white to grey mid-level signal in T1-weighted scans.[10] This permits visualization of the articular disk and the pharyngeal airway. Valuable information about the position and morphology of the disk can be acquired, making MRI the gold standard for imaging of the TMJ, and setting it apart from CBCT which lacks this information.[2]

In a study done by Tymofiyeva et al., MRI was determined to be well suited for three-dimensional localization of impacted teeth without the use of a contrast agent. This is because of the contrast observed between the teeth and surrounding signal-giving tissue, such as bone marrow, gingival tissue, tongue, cheeks, and saliva.[17] MRI has also been useful in pre-surgical implant planning, visualization of accessory canals, and nerve mapping.[15,18,19]

The use of MR imaging in orthodontics presents disadvantages such as limited access to and availability of MR scanners, increased cost, and longer imaging times. Additionally, hard tissues, including the teeth, transmit a very low signal on T1-weighted images, resulting in inferior visualization on the MR image. Another disadvantage is metal induced image distortions, making MR imaging difficult in orthodontic patients with fixed metal appliances. Contraindications of MRI include claustrophobia, cardiac pacemakers, implanted cardiac defibrillators, metallic foreign bodies in the eyes, retained ferromagnetic surgical clips, or patients in the first trimester of pregnancy.[2,15,17,20] A full medical history should be taken prior to an MRI scan to avoid patient harm.

Measures have been taken to reduce the disadvantages of MR imaging. Research shows that ceramic brackets can be used without causing distortion of MR images.[20] Therefore, the use of ceramic brackets could make MR scans a viable method of orthodontic imaging at all stages of treatment. Additionally, the contrast-enhanced MR technique was developed to aid in improving visualization of the dentition.[21] This technique uses an intraoral contrast media to overcome the difficulty associated with distinguishing the crowns of teeth on an MR image. A study by Gray et al., presents evidence that the availability of MR scanners is increasing while the cost is decreasing.[15]

The field of orthodontics relies heavily on diagnostic imaging for treatment planning. The highest level of diagnostic information is derived from 3D images. Available methods for 3D orthodontic imaging include CBCT and MR imaging. The detrimental effects associated with potentially high levels of ionizing radiation exposure associated with orthodontic treatment has led to increased concern among the public. This concern is exacerbated because growing children and adolescents - who exhibit increased radio-sensitivity - are the majority of the patient population. Thus, MR imaging provides the safest method of 3D imaging for orthodontic patients. As continued progress is made to minimize the disadvantages, it may present itself as the preferred method of imaging in orthodontics.

CHAPTER TWO

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

Abstract

Objective: The aim of this study is to compare tooth length measurements made on cone beam computed tomography (CBCT) scans and 3-Tesla (3T) magnetic resonance (MR) scans.

Materials and Methods: One CBCT scan (NewTom3G, AFP Imaging, USA) and one 3T MR scan (Siemens Medical Solutions, DE) as performed on 12 subjects. CBCT images were captured with an 18x16 inch field of view that covered the whole head. Contiguous sagittal MR images of the whole head were produced in a 3.0T imaging system with a T1-weighted 3D imaging sequence (Magnetization Prepared Rapid Acquisition by Gradient Echo (MP-RAGE), TP/TE = 1950/2.26 ms) and isotropic resolution of 1.0x1.0x1.0 mm. DICOM formatted images from each scan were oriented in all three planes of space and 4 mm thick slices were made through the long axis of all permanent teeth. Tooth length measurements were determined from the slices (336 tooth length measurements) using Invivo (v.5.4) imaging software (Anatomage Inc., San Jose, CA).

Results: Overall data showed good correlation with Intraclass Correlation Coefficient of 0.981 ($P<0.001$) and Pearson's Correlation of 0.981 ($P<0.001$). The mean difference between the collective measurements was 0.04 mm ± 0.77 mm. Measurements in the maxilla (ICC 0.982) had slightly higher correlation than those in the mandible (0.980).

Second premolars were found to have the highest correlation of all tooth types (ICC 0.984, P<0.001).

Conclusions: Measurements made of 3T MR images have good correlation with equivalent CBCT measurements. Larger sample size is required to evaluate differences found in data. Future studies are required to evaluate MRI as a diagnostic imaging modality in the field of orthodontics.

Introduction

Imaging plays an essential role throughout the treatment of an orthodontic patient. There are multiple time points that require several radiographic images to be taken for the purposes of diagnosis and treatment planning. Traditionally, these have included lateral cephalograms, panoramic radiographs, and full mouth surveys consisting of several periapical and bitewing images. 2D imaging techniques present several disadvantages, most significantly reducing a three-dimensional (3D) object to a two-dimensional (2D) view. As a result, tissue overlapping, landmark obstruction, distortion, magnification and object displacement occur.[2,3,6] For this reason, over the past two decades these images have become increasingly supplemented by 3D imaging technologies, in particular cone beam computed tomography (CBCT).[8]

Today, CBCT is the gold standard of 3D imaging in orthodontics. The data collected from these images has proven to be crucial in complex cases involving impacted teeth, airway, temporomandibular joint disorders, asymmetries, and other craniofacial anomalies.[2,3,5,6,8,22] While these images are indisputably valuable, the increased exposure of orthodontic patients to ionizing radiation is of concern. Long-term stochastic effects of ionizing radiation include increased risk of radiation-induced carcinogenesis. [1,7,8,11,12] In accordance with the ALARA principle, a radiation-free imaging technique should be considered to eliminate such risks.[1,7,14]

Magnetic resonance imaging (MRI) is a technology that yields 3D imaging of the head and neck area without exposing patients to ionizing radiation, and is the highest contrast resolution medical imaging technique.[2] MR images provide visualization of both hard and soft tissue structures including the temporomandibular joint (TMJ), articular disk, pharyngeal airway, and head and neck musculature.[15,16,18,23,24] Additionally, studies find MRI is accurate in localizing impacted teeth.[16,17] These structures are of interest to orthodontists, but are often not visible or not measurable using conventional imaging technologies. Images are obtained with radiofrequency (RF) radiation in the presence of carefully controlled magnetic fields.[16] The machine achieves a resonance signal from hydrogen nuclei (protons) in water and fat.[2,16] RF pulses stimulate hydrogen atoms, which emit energy that is converted to numbers. These numbers are processed on a computer and converted into an image. Essentially MRI is imaging water molecules in the tissue.[2,16] The differential densities of protons and the molecular environment influence the relative intensities of the MR signal generated, producing distinction between various tissues.

MR imaging sequences can be divided into two groups: T1- or T2-weighted. T1-weighted have a longitudinal proton relation time, and T2-weighted have a transverse proton relation time.[15] The contrast between the two types enables the T1-weighted image to depict normal anatomy, while T2-weighted images are used to detect infection, hemorrhage, and tumors.[15] Typical orthodontic diagnosis can be completed using T1-

weighted images. In T1-weighted images, tissues with low concentration of protons produce a low signal and appear radiolucent. Conversely, high concentration of protons create a strong signal and appear very bright, as seen with the fatty bone marrow of cancellous bone.[15] The ability to accurately interpret MR images is critically important because it is considerably different from traditional radiographs.

As with any imaging technique, MRI presents certain disadvantages including increased cost, longer imaging times, limited access and availability of MR scanners, and metal induced image distortions.[2,16,20,25] Additionally, inferior visualization of hard tissues may occur, resulting in increased difficulty distinguishing dentition in images.[16] MRI is contraindicated in patients with claustrophobia, cardiac pacemakers, implanted cardiac defibrillators, metallic foreign bodies in the eyes, retained ferromagnetic surgical clips, and during the first trimester of pregnancy.[2,15,20,25,26] A full medical history should be taken prior to an MRI scan to avoid patient harm.

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, patients’ exposure to ionizing radiation may be decreased through utilization of MR images to perform orthodontic diagnosis. Thus, minimizing the risk of radiation induced carcinogenesis.

Materials and Methods

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. Thirteen human subjects participated in this study, each being a new patient in the Loma Linda University School of Dentistry (LLUSD) graduate orthodontics clinic. Patients were selected based on their willingness to participate in the study and lack of exclusion criteria. Exclusion criteria included 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. One subject was eliminated during data collection because movement artifacts were present in the CBCT scan. The remaining patients' age ranged from 12 years and 1 month to 31 years and 5 months, with the average age being 15 years and 11 months. Seven subjects were male and five were female.

One CBCT scan (NewTom 5G, AFP Imaging, USA) and one 3T MR scan (Siemens Medical Solutions, DE) without intraoral contrast media was performed on each subject. All scans were performed within two weeks of one another, prior to the placement of orthodontic separators or appliances. CBCT images were acquired with a 18x16 inch field of view that covered the entire head. Contiguous sagittal MR images of the whole head were created in a 3.0T imaging system with a T1-weighted 3D imaging sequence (Magnetization Prepared Rapid Acquisition by Gradient Echo (MP-RAGE), TR/TE = 1950/2.26 ms) and isotropic resolution of 1.0x1.0x1.0 mm. Scan time was less than 4 minutes. Digital Imaging and Communications in Medicine (DICOM) formatted images were constructed from both scans and the volumes were oriented in all three planes. 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. Next, volumes were oriented in the transverse plane so a line connecting the widest points of the maxillary sinuses were parallel to the horizon. Lastly, the volumes were oriented in the sagittal plane such that a line connecting the anterior nasal spine (ANS) to posterior nasal spine (PNS) was parallel to the horizon. Tooth length measurements were made from 4 mm thick slices made through the long-axis of all permanent teeth (336 tooth length measurements) using Invivo (v.5.4) imaging software (Anatomage IC., San Jose, CA). Four week intervals were implemented between measurements on each scan. Measurements on CBCT scans were completed prior to MRI.

Incisor slices were aligned with the long axis, through the center of the incisal edge and root apex, and perpendicular to 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. Premolar slices were aligned through the buccal cusp tip and buccal root apex. In addition, premolar slices were made perpendicular to a line through the central groove. Molar slices were oriented through the mesio-buccal cusp tip and the mesial root apex and perpendicular to a line through the central groove.

All permanent teeth, including non-erupted teeth, were measured with the exception of third molars. No primary teeth were measured. Incisor teeth were measured from the incisal edge to the most superior point of the root for maxillary anteriors and to the most inferior point of the root for mandibular anteriors. For canines, measurements were made from the cusp tip to root apex. Premolars were measured from the buccal cusp tip to the most superior point of the buccal root (if multiple roots were present) for maxillary premolars and the most inferior point of the root for mandibular premolars. Maxillary molars were measured from the mesio-buccal cusp tip to the most superior point of the mesio-buccal root. Mandibular molars were measured from the mesio-buccal cusp tip to the most inferior point on the mesial root.

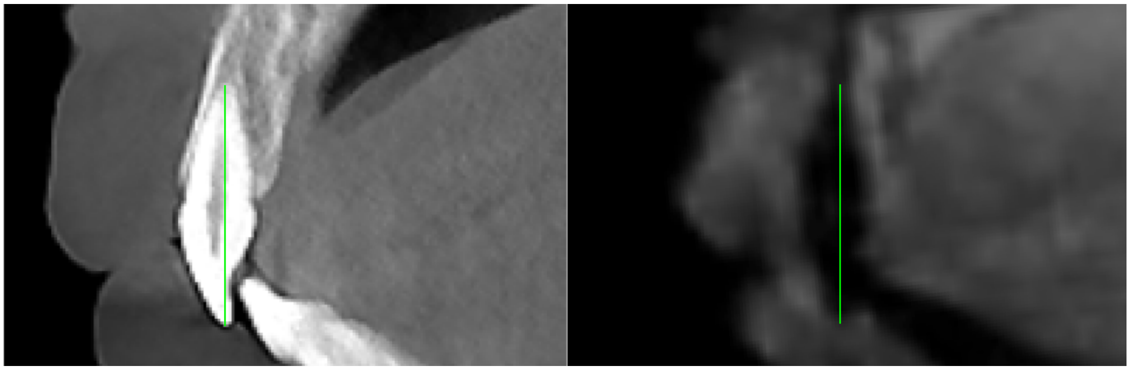

Figure 1. Measurement of an incisor. Shown here is a maxillary left central incisor on CBCT slice (left) and MRI slice (right). Maxillary incisors were measured from the most inferior point on the incisal edge to the most superior point on the root.

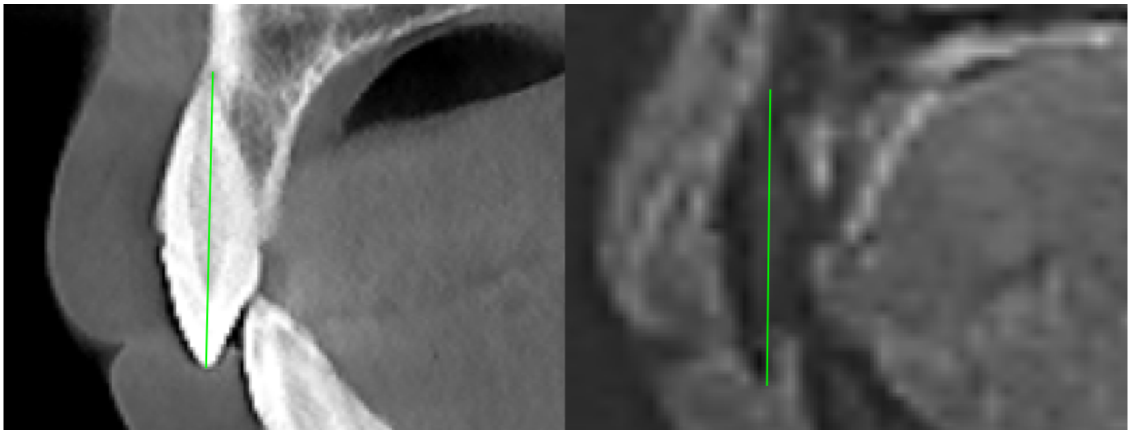

Figure 2. Measurement of a canine. Shown here is a maxillary right canine on CBCT slice (right) and MRI slice (left). Maxillary canines were measured from the most inferior point on the cusp tip to the must superior point on the root

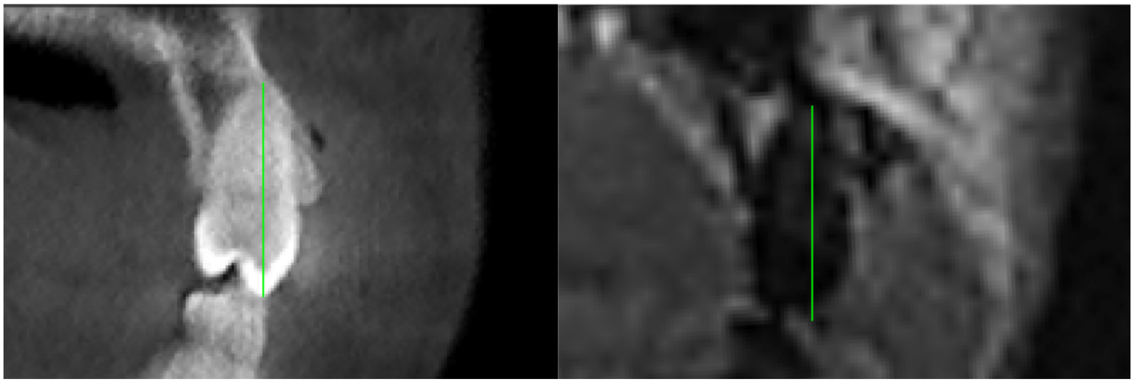

Figure 3. Measurement of a premolar. Shown here is a maxillary left premolar on CBCT slice (left) and MR slice (right). Maxillary premolars were measured from the most inferior point on the buccal cusp tip to the most superior point on the buccal root (for teeth with multiple roots).

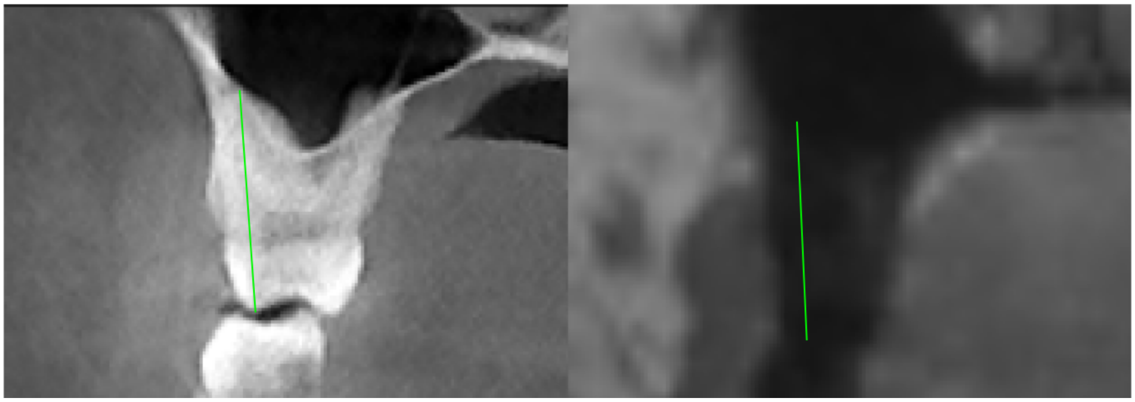

Figure 4. Measurement of a molar. Shown here is a maxillary left molar on CBCT slice (left) and MR slice (right). Maxillary molars were measured from the most inferior point on the buccal cusp tip to the most superior point on the buccal root.

Results

A total of 336 tooth length measurements were taken. Of the 336 measurements, 28 were taken on non-erupted teeth. Normality tests were performed to analyze the distribution of data. Kolmogorov-Smirnov found both CBCT (D=0.041, P=0.200) and MRI data to be normally distributed (D=0.045, P=0.097). Pearson's correlation and Intraclass Correlation Coefficient (ICC) were used to analyze the agreement of the combined data. Overall agreement between tooth length measurements made on CBCT and MR images was high with a Pearson's correlation of 0.981(P<0.001) and ICC of 0.981 (P<0.001) (Table1). ICC for all categories evaluated in this study are listed in Table 1 and Table 2. Differences between the two images were minimal with a mean difference of 0.04 mm ± 0.77 mm (Table 3).

Reliability of measurements was tested by re-measuring tooth lengths for four subjects on CBCT and MR images at four week intervals following the original measurements. Reliability was very high for CBCT and high for MRI. For CBCT, Cronbach's Alpha was .995 (P<0.001) and ICC was 0.989 (P<0.001). MRI had a Cronbach's Alpha of 0.926 and ICC of 0.862 (P<0.001).

Table 1. Intraclass Correlation Coefficients for all teeth, maxillary and mandibular arches, and tooth types. (95% confidence level)

CATEGORY	ICC	LOWER BOUND	UPPER BOUND	P-VALUE (α =0.05)
ALL TEETH	0.981	0.976	0.984	<0.001
MAXILLARY	0.982	0.974	0.987	<0.001
MANDIBULAR	0.980	0.973	0.985	<0.001
CENTRAL INCISORS	0.964	0.937	0.980	<0.001
LATERAL INCISORS	0.943	0.900	0.968	<0.001
CANINES	0.961	0.930	0.978	<0.001
FIRST BICUSPIDS	0.980	0.964	0.989	<0.001
SECOND BICUSPID	0.984	0.971	0.991	<0.001
FIRST MOLAR	0.910	0.845	0.949	<0.001
SECOND MOLAR	0.941	0.896	0.966	<0.001

Additionally, results were broken down into maxilla vs. mandible, tooth type (Table 1), and individual teeth (Table 2). Measurements in the maxilla were highly correlated (ICC 0.982, P<0.001), while those in the mandible showed slightly less agreement (ICC 0.980, P<0.001). Second premolars showed the most agreement of any tooth category with an ICC 0.984 (P<0.001). First molar measurements showed the least agreement among tooth categories with ICC 0.910 (P<0.001). Agreement for individual teeth ranged from 0.754 (P=0.002) for tooth #3 to 0.997 (P<0.001) for tooth #29.

Table 2. Intraclass Correlation Coefficients of Individual Tooth Numbers.

TOOTH #	ICC	LOWER BOUND	UPPER BOUND	P-VALUE (α=0.05)
2	0.864	0.602	0.959	<0.001
3	0.754	0.340	0.923	0.002
4	0.968	0.892	0.991	<0.001
5	0.979	0.929	0.994	<0.001
6	0.985	0.948	0.996	<0.001
7	0.890	0.597	0.969	<0.001
8	0.922	0.750	0.977	<0.001
9	0.949	0.834	0.985	<0.001
10	0.968	0.894	0.991	<0.001
11	0.980	0.936	0.994	<0.001
12	0.987	0.958	0.996	<0.001
13	0.988	0.959	0.996	<0.001
14	0.924	0.760	0.977	<0.001
15	0.973	0.908	0.992	<0.001
18	0.953	0.849	0.986	<0.001
19	0.922	0.756	0.977	<0.001
20	0.986	0.931	0.996	<0.001
21	0.970	0.903	0.991	<0.001
22	0.888	0.474	0.971	<0.001
23	0.951	0.842	0.985	<0.001
24	0.979	0.933	0.994	<0.001
25	0.980	0.925	0.994	<0.001
26	0.990	0.967	0.997	<0.001
27	0.948	0.832	0.985	<0.001
28	0.982	0.941	0.995	<0.001
29	0.997	0.991	0.999	<0.001
30	0.971	0.905	0.992	<0.001
31	0.975	0.919	0.993	<0.001

Table 3. Mean difference (mm) of MRI-CBCT for all teeth, maxillary and mandibular arches, and tooth types with 95% confidence level.

CATEGORY	MEAN DIFFERENCE (MM)	SD (MM)
ALL TEETH	0.04	0.77
MAXILLARY	-0.10	0.84
MANDIBULAR	0.18	0.65
CENTRAL INCISORS	0.03	0.73
LATERAL INCISORS	-0.16	0.70
CANINES	0.24	0.85
FIRST BICUSPIDS	0.06	0.65
SECOND BICUSPID	0.14	0.61
FIRST MOLAR	-0.02	0.76
SECOND MOLAR	-0.01	0.99

Table 4. Mean difference (mm) of MRI-CBCT for individual teeth with a 95% confidence level.

TOOTH #	MEAN DIFFERENCE (MM)	SD (MM)
2	-0.59	1.33
3	-0.13	1.05
4	-0.03	0.95
5	0.07	0.78
6	0.02	0.70
7	-0.62	0.94
8	-0.03	1.00
9	0.03	0.80
10	-0.09	0.57
11	-0.20	0.67
12	-0.14	0.55
13	0.19	0.51
14	0.10	0.85
15	0.02	0.73
18	0.38	0.98
19	-0.11	0.67
20	0.34	0.50
21	0.12	0.74
22	0.74	0.88
23	0.13	0.67
24	-0.16	0.54
25	0.28	0.51
26	-0.05	0.29
27	0.39	0.88
28	0.22	0.54
29	0.04	0.28
30	0.05	0.37
31	0.15	0.60

Discussion

The purpose of this study was to compare the accuracy of tooth length measurements made on CBCT and MR images. Measurements made on these images showed good correlation with equivalent measurements taken from CBCT images (ICC 0.981, $P < 0.001$. Measurements taken in the maxilla had a higher ICC (0.982, $P < 0.001$) compared to those in the mandible (0.980, $P<0.001$). One possible explanation could be the bony makeup of each jaw. The larger quantity of spongy bone found in the maxilla allows for better visualization of the root on MR images, thus leading to more accurate measurements.[17]

The mean difference of MRI-CBCT was calculated for all measurements, maxilla vs. mandible, tooth categories, and individual teeth (Table 3). For all teeth, a statistically significant mean difference of 0.04 mm ± 0.77 mm was observed. The clinical significance of this difference is unknown and requires further investigation. However, clinicians should be aware of this difference when making the decision to use MR images in lieu of CBCT. Canines showed the largest mean difference between tooth types (0.24 mm ± 0.85 mm). This finding could be due to the difficulty identifying cusp tips on MR images.

In a study done by Taylor[27], tooth lengths on MR images were also evaluated. Results indicated near perfect correlation between CBCT (ICC 0.998, $P<0.001$) and MR images (ICC 0.970, $P<0.001$).[27] Results were further broken down into maxilla vs. mandible, tooth type, erupted vs. non-erupted, and individual teeth. The results they obtained reflected trends observed in the current study, with the first molar showing the least amount of agreement (ICC 0.824, $P<0.001$) and the second premolar showing the most agreement (ICC 0.957, P<0.001). Higher agreement among maxillary measurements compared to those in the mandibular arch was also consistent in both studies. The previous study was conducted with an unknown washout protocol which could introduce bias in the data. Without a sufficient washout period the results could be artificially skewed. The current study was conducted with a strict four-week washout period during which the researcher was able to disremember previously collected data and minimize biases. This may explain the lower overall mean difference found in the study by Taylor[27] (0.03 mm ± 0.11 mm).

Table 5. Intraclass Correlation Coefficients for studies by Piano and Taylor[27].

CATEGORY	PIANO	TAYLOR[27]
ALL TEETH	0.981	0.956
MAXILLARY ARCH	0.982	0.965
MANDIBULAR ARCH	0.980	0.945
CENTRAL INCISORS	0.964	0.916
LATERAL INCISORS	0.943	0.923
CANINES	0.961	0.922
FIRST PREMOLARS	0.980	0.926
SECOND PREMOLARS	0.984	0.957
FIRST MOLARS	0.910	0.824
SECOND MOLARS	0.941	0.927

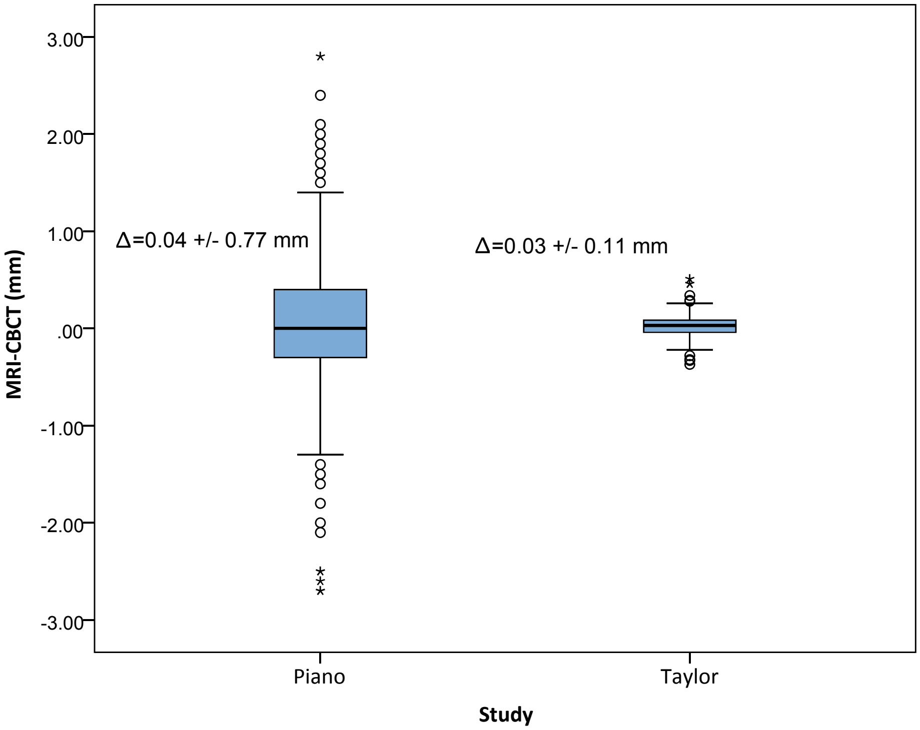

Figure 5. Mean Difference of MRI-CBCT (mm) and SD of Differences (mm) for studies by Piano and Taylor[27]

Although agreement among measurements was found to be good under the conditions of this study, the ability to distinguish the dentition and other hard tissues on a constructed cephalogram may be problematic. In turn, practitioners may encounter difficulty in employing MR images for treatment planning and diagnosing in the field of orthodontics. Improving the visualization of the dentition on MR images is crucial in overcoming this deficiency. Utilizing a proton-rich intraoral contrast media during imaging may prove to be a viable solution and should be further investigated. Additionally, larger sample sizes are required in order to more accurately assess the potential of MR images as an alternative to CBCT in orthodontics.

Conclusions

1. Tooth length measurements made on MR scans show good correlation with tooth length measurements made on CBCT scans (ICC 0.981, $P<0.001$).
2. The mean difference between tooth length measurements made on MR & CBCT images was small (0.04±0.77 mm, $P<0.001$).

CHAPTER THREE

EXTENDED DISCUSSION

Many clinicians argue the amount of exposure from dental radiographs is minimal and clinically insignificant. However, stochastic effects can result from very low exposure and there is currently no evidence of a threshold dose. According to the 2007 recommendations of the International Commission of Radiological Protection (ICRP), the incidence of cancer due to ionizing radiation increases linearly with the effective radiation dose at a rate of 5% per Sievert.[28] A higher effective dose is associated with CBCT compared to conventional images required for orthodontic treatment.[14] Additionally, it has been estimated that "one excess cancer fatality may be expected from every 17,000 CBCT examinations made with a CB Mercurary (facial FOV maximum quality)."[7] Because of this there are principles and guidelines in place to limit exposure and ensure judicious use of imaging modalities exposing patients to ionizing radiation. It is of utmost importance for the dentist to carefully consider the justification for every exposure and aim to optimize each examination.[7] Ultimately, clinicians, guardians, and patients must either accept the increased risk of cancer or endure the increased cost and diagnostic limitations associated with MRI.

A major drawback to MRI is poor visualization of hard tissues including bony structures and the teeth. Air interface between the detention and soft tissues creates difficulty in identifying detention. Therefore, if this interface is reduced or avoided, the visualization of teeth is possible.[17] Proton-rich topical oral contrast media, ranging from water to various gadolinium-base substances,[17]may be utilized to aid in distinguishing teeth on MR images. Topical oral contrast medias surround the teeth with a substance saturated in hydrogen ions, enhancing the contrast between the two and facilitating their identification on the image.[21,29]

The ideal intraoral contrast media is biocompatible intraorally, easy and efficient to use, safe to use in MRI environment, emits a high intensity signal on MR images, and is readily available and affordable. Substances such as water, fluorine coating, blueberry juice, and ferric ammonium citrate (FAC) have been used as intraoral contrast mediums in a number of studies.[19,21,24,29] One approach advises holding an intraoral contrast medium, such as water or blueberry juice, in the mouth while maintaining a prone position during the scan.[21,23] This method can be uncomfortable for the patient, and is subject to imaging artifacts due to movement of the liquid intraorally. Other studies have employed superimposing multiple MRIs in order to indirectly visualize the incisors, but superimposition errors often occur.[18 21 29]

Ventura et al., conducted a study in which “a 2mm molded silicone mouthpiece for the upper jaw was fabricated and lightly coated with petroleum jelly in order to facilitate MRI based qualitative and quantitative analysis concerning speech articulation.”[29] Petroleum jelly is a hydrophobic hydrocarbon, which is insoluble in water and provides high intensity signal on T1-weighted images, making it an effective intraoral contrast medium. Ventura et al., concluded that this approach allows for visualization of the teeth in both static and dynamic MRI acquisitions during speech production, and is both feasible and affordable.[29] Successful implementation of this technique could support the use of MRI as the preferred imaging technique in orthodontics.

Another potential method involves utilizing a wax bite during the MRI scan. Dental waxes are composed of mainly hydrocarbon molecules combined with variations of gums, fats, fatty acids, oils and resin to modify their properties. A study done by Nakashima et al., investigated whether or not cerumen impaction is observable using MRI. Their study showed that on T1-weighted images, cerumen is visualized as a structure with high signal intensity.[30] Using base plate wax between the dentition during MRI scans may prove to be a viable method of improving visualization of the teeth, while minimally opening the bite.

Enhancing the visualization of the dentition using an intraoral contrast medium, and thus demonstrating increased accuracy of tooth length measurements on MR images can substantiate the notion that other length and angle measurements required for orthodontic diagnosis can be extrapolated for use in orthodontic treatment planning. Consequently, providing clinicians with a diagnostic image of full volumetric morphology without exposing patients to the harmful effects of ionizing radiation. This is particularly relevant for repeated examinations of children.[17] Future studies should be conducted to examine the effectiveness of intraoral contrast media in improving visualization of the teeth during MRI.

MR imaging provides unique diagnostic information regarding soft tissues that cannot be derived from CBCT. Specifically, information regarding the musculature of the head and neck, and soft tissue structures associated with the TMJ. Soft tissue influences on growth and development of the dentition and other facial structure are important to the discipline of orthodontics. As the orthodontic field trends towards a soft-tissue focus, future studies using MR data may prove to be invaluable to the advancement of the profession.

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APPENDIX A

TOOTH LENGTH MEASUREMENTS (MM) MADE ON CBCT SCANS.

TOOTH #	PT #1	PT #2	PT #3	PT #4	PT #5	PT #6	PT #7	PT #8	PT #9	PT #10	PT #11	PT #12
2	19.1	22	16.2	14.6	19.3	19.9	18.1	15.8	17.9	13	20.4	18.8
3	19.7	23.6	21.3	18.5	21.8	20.2	18.7	20.7	22.8	20.9	18.5	21
4	19	25.9	23.7	20.1	20.1	20.2	18.6	17.2	22.5	12.7	22.9	18
5	20.4	28.1	24.3	19.6	20.4	22.3	19.2	20.1	22.8	14.2	21.4	15.3
6	28.1	33.4	33.8	25.2	29.2	29.8	24	25.1	28	19.1	28.2	29
7	25.2	29.5	27.4	21.4	26.2	25.2	22.1	24	23.3	24.9	23.5	22.7
8	26.3	30.4	28.2	23.3	24.6	26.8	22.2	22.6	25.5	24.9	24.3	23
9	24.5	30	28.2	23.3	22	26.9	22.5	23.1	26.6	26	24.1	23.6
10	23.7	28	27.3	22.3	25.4	26.1	22.1	23.4	23.9	20.2	22.6	22.4
11	29	33	30.1	25.4	28.1	28.6	25.7	24.5	28.8	20	28.2	28.7
12	20.8	28.7	23.8	20.4	20.4	22.3	19.9	21.8	22.8	14	23.5	23.3
13	19.1	25.4	23.5	19.3	20.2	21.5	20.2	19.2	22.3	11.2	19.9	20.4
14	19.7	24.3	22.8	18	20.7	20.7	18.7	21.1	22.3	18.8	18.2	20.7
15	19	23.1	16.7	14.8	20.4	18.7	19	16.5	18.6	10.4	19.7	18.3
18	18.3	21.2	19.7	15.3	21.4	20.2	17.1	14	19.4	10.1	21.3	20.9
19	20.2	23.1	22.8	19.2	23	22.7	18.4	23.5	22.3	23.3	20	22.4
20	18.8	24.2	22.5	18.4	19.5	22.8	17	18.9	23.7	11.7	21.8	21.7
21	21	26.4	22.7	23.8	22.2	26	20.9	21.3	22.6	14.8	23	24.3
22	24.8	29.7	27	24.9	27.3	26.9	24.7	26.2	27.8	20.7	27.1	27
23	19.9	26.2	26.7	22.2	22	24	22.5	24.3	23.7	27	23	26.1
24	17.7	24.8	24.9	21.7	22	24	19.9	24.8	23.1	27.8	22.9	24.6
25	17.7	25.5	26.1	19.8	21.7	23.1	20	24.3	22.3	27	22.4	24.6
26	21.5	26.4	26.7	21.7	22.5	24	22.2	24.6	26.7	27	23.2	24.9
27	26.2	31.9	26.7	23.6	26.7	27.7	25	27.2	27.8	20.3	27.1	26.7
28	20.7	26.2	23.6	19.3	23.3	23.2	20.3	22.4	22.9	15.1	23.9	24.3
29	18.4	25.3	22.4	19	20.6	22.3	17.8	19.6	22.5	11.2	22.9	23.4
30	22.3	24.2	23.7	21.2	21.7	22.8	18.7	22.7	21.9	22	20	23.1
31	18.1	22.1	18.9	16.6	18.1	19.8	17.3	15.9	19.5	11.7	20.4	20.4

APPENDIX B

TOOTH LENGTH MEASUREMENTS (MM) MADE ON MRI SCANS.

TOOTH #	PT #1	PT #2	PT #3	PT #4	PT #5	PT #6	PT #7	PT #8	PT #9	PT #10	PT #11	PT #12
2	19.7	22.3	13.5	14.6	19.7	18.7	18	15.2	18.8	13.4	17.8	16.3
3	20.5	21.5	21	18.6	21.6	20.6	18.6	22.6	21.4	20.8	19	19.9
4	19	25.9	24.3	19.9	20.2	20.7	17.6	17	22	11.3	22.3	20.4
5	20.4	27.6	24.2	19.9	19.9	21	18.7	20.5	23.1	14.6	23.3	15.7
6	28.5	32.7	33.3	25.3	29.2	29.6	24.6	25.1	29.2	20.1	27	28.5
7	25.6	28.7	27.2	21.4	24.4	23.6	22	21.4	23.7	24.3	23.6	22.1
8	25.3	30	28.8	23.3	23.1	26.3	24.2	22.9	26.6	24.1	24.9	22.2
9	24.9	30.4	28.3	23.3	22	26.2	23.9	23.3	26.5	24	24.6	23.8
10	24.4	27.6	27.1	22.1	25.4	24.8	22.4	23.2	23.2	21	22.6	22.5
11	28.9	33.3	30.9	24.6	28.6	28.3	25	24.7	28.1	19.8	26.6	28.9
12	20.3	29.2	23.9	20.5	20.2	22.3	20	21.8	22	14.3	23.7	21.8
13	20.1	25.2	23.3	19.2	20.2	21.6	19.6	20.4	22.3	11.6	20.3	20.7
14	20.1	24.6	22.9	18.3	21	22.7	18.1	21.8	21.4	17.4	18.2	20.7
15	19.2	22.4	16.8	14.2	20.5	18.7	19.6	17.5	17.5	11.8	19.5	17.7
18	18.6	20.1	20.7	16.2	21	21.7	17.7	14.6	20.6	11.8	20.8	19.7
19	20.6	21.5	22.4	19.1	23	22.5	19.7	23.5	22.6	23	19.7	22
20	19.1	23.7	22.7	18.4	19.9	23.3	17.8	20.1	23.7	11.9	22.9	21.6
21	20.9	26.3	22.6	23.5	22.2	25.4	21.5	21.9	24.4	14.8	23.7	23.2
22	25.3	30.4	27	25.1	28.2	27	25.6	29	27.3	21.2	29	27.9
23	20.9	26.7	26.8	22.2	22.9	24	22.2	24.3	23.1	27	24.1	24.9
24	17.8	24.9	25.4	21.6	22.5	22.6	19.2	24.9	23.1	27.4	22.3	24.6
25	17.8	25.6	26.7	20.1	22.5	23	19.9	24.2	23.9	27	22.6	24.5
26	21.2	26.3	26.7	21.6	22.9	23.7	22.2	24.5	26.1	27	23.7	24.9
27	28.3	31.6	27	24.1	27	28	26.1	27.1	27.9	18.8	27.8	27.9
28	20.9	27.3	23.7	20.6	23.3	23	20.3	22.7	22.4	14.8	24.5	24.3
29	18.3	25.9	22.4	19.4	20.6	22.1	18.1	19.4	22.5	11.2	23	23
30	22.4	24.8	23.7	21.3	21.6	23	19.2	22.5	21.8	21.9	20.4	22.3
31	18.3	22.5	18.8	16	18.4	20.7	17.7	15.5	18.7	13	20.3	20.7