CASE WESTERN RESERVE UNIVERSITY

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THE RELIABILITY AND ACCURACY OF DENTAL ARCH MEASUREMENTS ON THREE DIMENSIONAL CONE BEAM COMPUTED TOMOGRAPHY SCANS

by

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Submitted in partial fulfilment of the requirements for the degree of Master of Science in Dentistry

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January 12, 2007

THE RELIABILITY AND ACCURACY OF DENTAL ARCH MEASUREMENTS ON THREE DIMENSIONAL CONE BEAM COMPUTED TOMOGRAPHY SCANS

Abstract

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Orthodontic study models are an integral part of the records required for proper diagnosis and treatment planning in orthodontics. Over the past decades, methods have been developed to generate three dimensional orthodontic study models in digital format. With the introduction of cone beam computed tomography to orthodontics, a new method exists to create three dimensional reconstructions of the human dentition. This study investigates the reliability and accuracy of dental arch measurements generated from these reconstructions.

The sample consisted of thirty dried human skulls. Each skull was scanned with the Hitachi CB Mercuray™ Cone Beam Computed Tomograph and a three dimensional reconstruction of the dentition was generated. Each skull was imaged once in maximum intercuspation, thus creating

A volumetric image of the entire skull. Using the computer program CB Works™ the maxilla and the mandible were manually segmented from the entire volume to generate separate volumes of each jaw.

Ten different direct measurements of the dentition of each skull were made with a high precision digital caliper. The same measurements were carried out on the three-dimensional digital reconstructions with the specialized commercially available software CB Works™.

Preliminary data analysis revealed a systematic error that lead to underestimation of the CBCT measurements by the size of a voxel. After adjustment for this error, final statistics were calculated. Reliability of all measurements was assessed by replicating the measurements on twelve skulls two times with the two measurement time points being one week apart. The intraclass correlation coefficient between the two measurement time points was calculated. Reliability for both the tested method and the control method was high ($r > 0.7$). Paired student's t-test was used to assess the accuracy of the new method compared to the gold standard, measurement with the digital caliper. Statistical analysis revealed a high correlation ($r > 0.7$) between

both groups. No statistically significant difference could be detected between both methods after adjustment for the systematic error.

Therefore, the investigated method appears to be useful for clinical and research purposes in orthodontics.

DEDICATION

This thesis is dedicated to:

God, for protecting me and guiding me through this world.

My mother Ileana who has supported me and provided strength in every situation. Thank you so much for everything you have done for me. I love you very much.

My brothers Florian and Costin who are my sunshine on cloudy days. Thanks for always standing behind me. May there be many good days ahead.

My grandfather Alexandru who is my idol and source of constant inspiration.

My grandmother Elena. I would not be what I am today without you.

Doro, for all the love you have given our family.

AKNOWLEDGEMENTS

Thank you Dr. Mark G. Hans for selecting me as an orthodontic resident at Case Western Reserve University, one of the finest teaching institutions in the world. You have created a unique combination of academic and clinical excellence, cultural diversity, and high moral values in your program. Thank you for letting me experience this. Thank you also for the motivation and guidance that you have provided as my thesis advisor. You are my "big daddy" of orthodontics.

Thank you Dr. J. Martin Palomo for being a good friend and teacher to me. You have awakened my interest in new technologies in orthodontics. Thank you also for all the input and guidance as part of my thesis committee. I highly appreciate your help.

Thank you Dr. Leena Palomo for becoming a member of my thesis committee and providing guidance, input, and motivation in all the critical situations.

Thank you Dr. Lysle E. Johnston for getting me interested in academics and showing me that "pointy headed academics" are cool after all. You have taught

me how to think, read, write, draw, and calculate in orthodontics. People are going to hate me for that.

Thank you Dr. Mohammad Razavi for being a great friend and mentor. From my first day here in Cleveland you have been like a brother to me. I will never forget that.

Thank you Mrs. LaVerne Vogel for taking care of the logistics in our department and aiding me in scheduling countless thesis committee meetings. Things would not have gone as smoothly without you.

Thank you Dr. Jed Hildebrand for being a great "big brother", neighbour, and work out partner. There are only few things we did not do together. Thanks for all the good times.

Thank you Dr. Clifford Lowdenback for being a great friend at all times. Thanks for introducing me to blue cheese and hot sauce.

Thank you to my class, the class of 2007. You made my time in Cleveland very special.

Thank you Dr. Jeffrey Kwong for being my brother in arms in this residency. Thanks for all the great ortho-related discussions, being a great study partner, inviting me to Toronto, being a great room mate. We

accomplished a lot and I will not forget the good times. Keep it up.

Thank you Dr. Alika Crew for being a great friend. Thanks for putting up with us guys day after day. This residency would have been boring without you.

Thank you Dr. Reid Wenger for being a great friend I could always depend on.

Thanks to Dr. Austin Phoenix, my orthodontic little brother, for helping out when necessary, and for putting up with all my crazy music.

Thanks to my orthodontic little sister, Dr. Cynthia Leung. You have made me a better teacher. Keep up the good work.

Thanks to all my other fellow residents that have made this residency so unique: Dr. John Ballrick, Dr. Eric Hughes, Dr. Boyd Martin, Dr. Kurt Kacer, Dr. Breyn Peters, and Dr. Wanvadee. Thanks for all the fun times we experienced during this residency. I highly appreciate your friendship.

Thank you very much to the incredible faculty of Case Orthodontics. You have created a unique learning environment by generously donating your time and knowledge to our program. This will never be forgotten.

You have inspired me and I am aiming to follow your example.

A special thank you to the great staff at our department. Amy, Shirley, Kim, Tina, Jessi, Niveen, you have made my everyday life so much easier and more pleasant.

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LITERATURE REVIEW

Orthodontic treatment is most successful when the maximum amount of information on the patient's condition is available to the clinician. Predictable results are based on a comprehensive diagnosis from which a detailed treatment plan is developed. Proffit (Proffit 2000) advocates the "problem-oriented" approach to orthodontic diagnosis that was originally developed in medicine to provide a rational protocol (Weed 1969) and adapted for use in orthodontics by Ackerman and Proffit (Ackerman and Proffit 1969). The decision-making process in orthodontic diagnosis and treatment planning involves the recognition of the characteristics of malocclusion and dentofacial deformity, the definition of the nature or cause of the problem, and the design of a treatment strategy based on the specific needs of the patient. Fundamental to this process is the acquisition of relevant information to form a data base. The information required for the diagnosis of a malocclusion is obtained from the clinical examination, photographs, radiographs, and study models.

In 2003, the American Association of Orthodontists

published a list of recommended basic orthodontic records in their Clinical Practice Guidelines for Orthodontics and Dentofacial Orthopedics (American Association of Orthodontists 2003). According to the AAO, pretreatment and posttreatment records should include extraoral and intraoral photographs, periapical and/or panoramic radiographs, cephalometric radiographs, and dental study models. Thus, study models are an integral part of the orthodontist's armamentarium. The information obtained from these dental casts is invaluable to help the orthodontist classify malocclusions, identify aberrations in tooth size, shape and position, and to formulate treatment objectives. As a static record of dental classification, models are used to visualize the morphology and position of the teeth in their respective dental arches, as well as the degree to which the teeth are malpositioned. In addition, individual teeth can be sectioned from the models and repositioned in wax to examine the feasibility of different treatment options. In fact, study models are the only three dimensional treatment record and therefore they are the major record used for treatment planning. In a study investigating how incremental information obtained from different types of

diagnostic records contributes to the determination of orthodontic treatment decisions Han et al. came to the conclusion that in over half of the cases the study models alone provided adequate information for treatment planning. Incremental addition of information from other types of diagnostic records made small differences (Han et al. 1991). This finding was in agreement with an article by Naccache et al., who found study models to be very useful in their computer-assisted orthodontic diagnosis (Naccache et al. 1989).

A study model is a precise three dimensional replica of a patient's teeth on which certain measurements can be performed easier and more accurately than in the patient's mouth. Some of these measurements are tooth size, the arch form and its dimensions, as well as tooth size-arch length discrepancies which are fundamental factors in the process of diagnosis (Proffit and Ackerman 2000). The model analysis is a time-consuming procedure. Nevertheless, it should be a vital part in the diagnosis and subsequent treatment planning process, for only through this method can the clinician gain true understanding of the nature of the malocclusion. However, in the day-to-day private practice setting, many

orthodontists seem to judge models subjectively, without applying analytical tests (Binder and Cohen 1998; Sheridan 2000).

Traditionally, measurements on dental casts are performed with the aid of either calipers, Boley gauges, or needle pointed dividers. Shellhart et al. concluded in their assessment of the Bolton analysis in crowded dentitions (crowding > three milimeters), using callipers and needle dividers, that a clinically significant measurement error (> 1.5 mm) can occur (Shellhart et al. 1995). Alternative methods of data acquisition and processing have been proposed in the past, but these methods demonstrated errors as well. Because direct measurement of three-dimensional objects have a high potential for error and variability, Schirmer and Wiltshire used photocopies of study models to compute mesio-distal tooth dimensions and analyse spacing and crowding with the rationale that measurements of a two-dimensional transfer are easier to obtain and can provide the same results. However, they concluded that even though photocopies are easier to handle than plaster models, making measurements on plaster models with calibrated gauges was the most accurate, reliable and

reproducible way of measuring (Schirmer and Wiltshire 1997). Champagne agreed with these results in his study and suggested that photocopies of dental casts were only suitable for the comparison of pre- and posttreatment archforms, to check original tooth rotations without having to retrieve the initial model, for communicating with other practitioners about some characteristics of a malocclusion, and for producing occlusograms for demonstration purposes (Champagne 1992). Not only did the method of photocopying the occlusal surfaces of dental casts prove to be less accurate, but it still required plaster models and therefore was associated with additional work rather than reducing the number of steps needed to generate a treatment plan. Ryden et al. introduced a new method for comparing tooth positions on dental casts at different stages. Holograms of dental casts that were created with a helium-neon gas laser were used for space analysis purposes. By superimposition of models of different time points it was also possible to assess changes in tooth positions in three dimensions. The investigated holographic system proved to be more accurate than previous alternatives, however it never proved to be practical in the clinical practice setting

(Ryden et al. 1982). Romeo presented a laser generated holographic system that was also able to deliver clinically useful data (Romeo et al. 1995). Photos and digitization of points proved to produce errors too. Lowley used the IMSCAN™ system (Lowley 1993) to digitize an image of the occlusal view of dental casts. A video camera linked to a computer captured the image, which was then displayed on a monitor. Specially designed software allowed the direct on screen measurements. He compared these measurements, which were obtained from a two dimensional system, to measurements with vernier callipers and a reflex microscope, which are in essence three dimensional systems for dental cast analysis. He arrived at the conclusion that the IMSCAN™ method was statistically less precise. He also found that errors in landmark identification were the largest source of error. Therefore, improving this task remains crucial in both the IMSCAN™ and the reflex microscope systems. Even three-dimensional systems do not eliminate the problems of landmark identification which occur when viewing the study cast from the occlusal surface (Lowley 1993). Mok and Cooke, using the DigiGraph™ Workstation for sonic digitization of dental casts, found that all measurements

obtained with this system overestimated the actual dimensions significantly. In addition, these measurements were not reproducible (Mok and Cooke 1998). Rossouw et al. compared three methods of measuring various fiducial points on dental casts. Using vernier callipers, a reflex metrograph, and calculated reflection holograms, they measured the distances between designated points on the dentition. Setting the level of significance at $p \leq 0.1$, they found that there was no difference among the different measurement methods. This means that holograms could be used as an orthodontic record, which would solve the problem of storing dental casts (Rossouw et al. 1991). Different factors may influence the accuracy and repeatability of measurements of individual teeth within the dental arch. Among these factors are an existing spacing condition, the inclination of the teeth, rotations, presence and location of interproximal contacts and anatomical variations (Zilberman et al. 2003).

With the increasing use of computers in the orthodontic office over the past twenty five years a greater number of digital multimedia applications have become available to the clinician and his staff to

facilitate standard procedures in practice and management - the ultimate goal being the "paperless" orthodontic office (McDavid et al. 1992; Scholz 1998). A report by an orthodontist who went through this process illustrates this evolution:

> "Several different options were explored that would allow for the digitalization of orthodontic records, but each method presented obstacles that would prove to be cost-ineffective and make data transfer so slow as to be impossible. Once more, we looked to the computer industry and the latest in computer technology to find the answers. I found a digital radiographic system and camera that would allow for storage directly on my hard drive. An automatic back-up system was set up on my server that continuously updates dual hard-drives of all patient radiographic and photographic records. I no longer need to worry about crashes or lost information as a result of the redundancy of the dual drives. A network of computers allows for easy viewing of photos and radiographs that have been transferred quickly and in a cost-effective manner." (Redmond et al. 2001).

After it was made possible to incorporate digital photos and radiographs into the electronic patient's file, the need for replacement of the plaster casts has emerged. Rossouw et al. already recognized this problem in 1991. This would be the next step in rationalizing the logistics of the records appointment, saving time, money and making storage space for plaster models obsolete. The developments in the field of laser technology coupled

with the rapid advances in computer technology created new opportunities for applications in orthodontics. More sophisticated methods were developed that were supposed to be superior to the rather rudimentary less successful approaches undertaken in preceding decades. Using the triangulation method, a group of Japanese researchers developed a system to scan and measure dental casts for treatment planning purposes in orthodontics. An innovation here was the possibility to analyse serial dental casts with the purpose of accurately assessing tooth movement in three dimensions. Depth and lateral resolution were 0.05 and 0.1 mm respectively (Yamamoto et al. 1989; 1991). Kuroda et al. presented a system for dental cast analysis composed of a measuring device with a slit-ray laser projector and two sets of coupled charged devised video cameras, an image processing unit, a 16-bit personal computer as a controller, and an engineering workstation as a post processor. The dental cast was projected and scanned with a slit-ray laser beam and in 40 minutes about 90,000 sets of X,Y, and Z coordinates were processed, resulting in measurements with an error of only 0.05 mm. However, a disadvantage of the slit-ray projection is the impossibility of sampling

beneath overhangs. It should also be noted that a parallax angle between the laser emitter and receiver causes a blind region around deep grooves, with an overhang (Kuroda et al. 1996). To minimize this system inherent problem, Motohashi and Kuroda (1999), using the same principle, invented a laser scanning technique that was somewhat more sophisticated. By combining two data sets taken from different scanner angles, it was possible to reduce the blind sector associated with undercuts in plaster casts. This system proved to have a wider range of application and could be used even with models of cleft lip and palate patients, which have a characteristically complicated palatal anatomy. This system, though promising, would have to be developed further, according to the authors, for routine clinical application. With the now existing high speed lasers, 3-D data can be acquired from dental casts if the model is scanned from multiple angles. With a commercially available apparatus, the entire shape of the upper and lower casts can be reconstructed, thus reproducing the characteristic structures. The data connections were satisfactory for the flat surfaces but less accurate for the inclined surfaces. If reconstruction of the occlusion

between the upper and lower casts can be accomplished, then these results could be useful for clinical applications such as computerized diagnoses and treatment of occlusion, and for the replacement of the stone casts in the dental office by computerized data (Sohmura et al. 2000). With the goal to reduce the cost and acquisition time of orthodontic data and facilitate the conduct of epidemiological studies, Alcaniz et al. (1998) presented a new system for three-dimensional orthodontic treatment planning and movement of teeth. It was a computer vision technique for the acquisition and processing of 3-D images of the profile of hydrocolloid dental imprints. Profile measurement was based on the triangulation method which detects deformation of the projection of a laser line on the dental imprints. Wakabayashi and coworkers developed a computerized system to analyze the functional and morphological harmonies of the tooth and dental arch, to measure a dental cast and to detect the apex of dental cusps and angle points of incisors which delivered acceptable results (Wakabayashi et al. 1997). Even an apparatus for intra oral direct scanning was created. It consisted of a pig-tailed laser with line generating optics, a stepping motor driven positioning stage, and a

commercial CCD (charge coupled device) camera system with frame grabber interface. This was coupled with a control personal computer and a mirror system. The mirror system compensated for the fact that there was no possibility of watching an object directly in the mouth under a certain angle except from a facial position during intra oral scanning. With this prototype, the size was still too large for intra-oral use, but the achieved level of accuracy proved to be sufficient for further development which should include a reduction in size and the use of more precise device components (Commer et al. 2000). Because laser based systems all have problems of analyzing areas in undercuts Sohmura et al. (2000; 2004) investigated the possibilities of using medical computer tomographic scanners to produce a three dimensional digital model of a dental cast. They noted that the scans were slightly smaller than the original objects and that the accuracy of representing the complicated morphology of a dental cast was slightly inferior to the newest generation of laser scanners. The advantage of this system was ease of use and improved accuracy in the undercut areas.

The aforementioned systems all had some significant

advantages. However, disadvantages such as the time needed to acquire data, high cost, or lack of precision, ultimately kept them from becoming widely used in private practice. With more sophisticated hard- and software solutions and a tendency for outsourcing in the orthodontic office, several companies now offer virtual study models. Out sourcing has made the routine use of digital models for the average clinician more attractive, simple and economic. Proprietary software for virtual model analysis is provided by the companies, giving the clinician valuable tools for almost any desirable application. Among these companies are such names as Invisalign™, OrthoCad™, and Geodigm™. Each company has a patented method of creating the electronic model, but in general there are three main principles of generating such three dimensional models: (1) destructive, (2) non-destructive imaging of a plaster cast, and (3) direct imaging of the impression. The protocol would be as follows. Impressions are taken in the orthodontist's office and are then mailed to the company. There, these impressions are poured in plaster, creating a physical model of the patient's dentition. This model is then imaged destructively or non-destructively. In destructive

imaging the removal of a thin layer of material alternates with an image capture, generating a multitude of images that are then combined and rendered in three dimensions. In non-destructive scanning a laser based system with a multi axis robot is used to gain different perspectives of the plaster model. These perspectives are then combined to render a three dimensional model. A different approach to non-destructive scanning involves the use of a micro computer tomogram to scan the plaster model. Alternatively, computer tomograms can also be used to scan the impression directly (Mah and Hatcher 2003). The protocol depends on the company and the preferences of the orthodontist. The three dimensional information is then sent to the orthodontist's office via the internet, where it can ultimately be accessed with the software supplied by the company. Models can be viewed in three dimensions and diverse parameters such as the occlusion, mesio-distal tooth size, Bolton's Ratio, arch length, arch width, overjet, and overbite can be analyzed (Quimby et al. 2003). Today these virtual model systems are so sophisticated that they can be used to design templates for indirect bonding or for fabricating orthodontic appliances. Also, virtual set-ups can be made according

to the orthodontist's instructions. OrthoCAD™ for example generates a 3-dimensional (3-D) model from a set of alginate impressions and a bite registration. Displaying the intraoral hard tissue morphology both in its original condition and after the set-up, the resulting 3-D model is transmitted electronically to the orthodontic office. With the OrthoCAD™ software installed locally, the clinician examines the 3-D model and makes any desired changes or creates a new setup. The software can also be used to visually compare different predicted treatment outcomes, suggest the most suitable appliances for the case, and fine-tune positioning parameters to ensure maximum performance (OrthoCAD™ 2006; Redmond 2004). Invisalign™, using computer-aided-design-computer-aided-manufacture (CAD-CAM) technology combined with laboratory techniques to fabricate a series of custom appliances that can move teeth from beginning to end. 3D virtual models are created from impressions, and, after the orthodontist has approved the treatment plan, the computer images are converted to physical models by using a process called stereolithography. These models are then used to fabricate the aligners on a Biostar™ pressure molding machine. Fabricating these aligners in an

orthodontic office would be a very time-consuming and labour-intensive process that probably would not be practical for everyday treatment (Wong 2002).

The ability of 3D virtual models to represent the patient's dentition accurately has been investigated and the validity and reproducibility of measurements on these models has been extensively studied. Tomassetti et al. evaluated different measuring methods, such as Vernier calliper measurements, QuickCeph™, Hamilton Arch Tooth System (HATS), and OrthoCad™ to calculate the Bolton tooth size analysis. The results from the OrthoCad™ analyses were slightly less correlated with the Vernier calipers results than were the HATS analyses. The range of measurements was greater for the OrthoCad™ than for the HATS or the Vernier caliper measurements. Therefore, OrthoCad™ had slightly less correlated results, and the differences were of a greater magnitude (Tomassetti et al. 2001). Zilberman et al. (2003) studied the validity of tooth size and arch width measurements on the three dimensional virtual OrthoCad™ models compared to measurements on conventional plaster models performed with digital calipers. Statistically significant differences were found. They were so minimal however,

that clinical significance is not given. The results prove the clinical validity and applicability of virtual three dimensional models. The digital calliper method however seems to be slightly more accurate and therefore should be preferred for scientific work. Quimby et al. (2004) tested the accuracy, reproducibility, efficacy and effectiveness of computer based and plaster models. Measurements made on computer-based models produced from plaster casts poured the day after the impressions were taken did not differ from those made on the gold standard except for mandibular and maxillary space available. Thus, for measurements made directly between two anatomical points on the computer-based models the accuracy was equal to that of plaster models. The process of measuring segments introduced error into the measurements. Except for overbite and overjet, the measurements made on the plaster casts and the virtual models were statistically different. But, for the majority of measurements, the magnitude of these differences was less than 0.5 mm, and therefore, may not be clinically significant.

The application of 3-D virtual study models in the orthodontic practice setting has great advantages over

the use of conventional plaster models. They are stored electronically, which means that the information will be stored on compact discs or computer hard drive space. Therefore virtual models consume virtual space instead of the physical space required to store plaster models. Storing plaster models has financial and logistic burdens for the orthodontist that create problems and increase overhead (Bell et al. 2003). Also, model retrieval is greatly facilitated because it can take place chairside at the click of a button. Communication with other dental specialties is significantly improved because the model can be sent to other offices via electronic data transfer. The traditional duplicating of plaster casts, handling and shipping has become obsolete. If a set-up is involved in the treatment planning process, using virtual models is more accurate and less labour intensive. The orthodontist can create his own set-up on the computer without needing a laboratory to duplicate the cast, saw the teeth into segments and then wax them in place. Treatment outcome can also be simulated and aid in patient instruction and education. Being less time consuming, easy to use, and very cost effective at comparable levels of clinical accuracy, a strong argument

can be made for the routine application of computer based three dimensional models (Garino and Garino 2002). It is no surprise therefore that at present approximately 10% of all orthodontists in Canada and the United States are utilizing digital models and this popularity is constantly increasing (Joffe 2004).

Despite all the advantages of virtual models, some time consuming and costly steps are still necessary to generate them. For example, precise impressions of the patient's dentition still have to be taken. Although alginate can be used to create virtual models the use of polyvinyl siloxane is recommended when appliances shall be fabricated from these impressions. This is due to the increased need for dimensional stability and detail in the impression (Invisalign™ 2005). Either the impressions or the resulting models have to be sent to the company for conversion to digital models. Both alternatives require some logistical effort. Diligence in handling and packaging the impressions or models is necessary.

Now that the practical applicability of virtual models has been proven, virtual models have become an important part of the modern orthodontic practice. However, additional streamlining of the process is still

desirable. The cost of the systems is still quite high and the impression techniques are more complex than traditional orthodontic impression. With further development of technology, it will be only a matter of time until costs come down. However, the acquisition of dental cast data is still an area of concern. The introduction of three dimensional digital volumetric radiography to the orthodontic practice may find application here.

The first FDA approved cone beam computer tomography scanner for dentistry in the United States was the NewTom™ Model QR-DTV 9000 which was followed by it's successor, the NewTom™ 3G. To date four machines with FDA approval exist in the United States: the NewTom™ Plus, the i-CAT™, J. Morita 3-D Accuitomo™, and the Hitachi CB Mercuray™. While the NewTom™ requires the patient to be positioned in a supine position similar to a medical CT, the i-Cat™, the Accuitomo™, and the Mercuray™ allow the patient to sit upright similar to a conventional dental panoramic unit. The Accuitomo™, however, is a unit specifically designed for imaging of single groups of teeth only and has a very limited area of application therefore. A comparison of the technical specifications

(Table 1) will illustrate similarities and differences among these four machines.

TABLE 1.--Technical Specifications of CBCT Machines

	Hitachi CB Mercuray©	NewTom 3G©	i-Cat©	J.Morita 3-D Accuitomo©
Scan System	Cone Beam	Cone Beam	Cone Beam	Cone Beam
X-ray tube voltage (kVp)	60,80,100, 120	110	128	60-80
X-ray tube current (mA)	10, 15	15 (maximum)	3-8	1-10
Field of View	6, 9, 12 inch	6, 9, 12 inch	6 / 9 inch	40 mm x 30 mm
Image output (bit)	12	12	12	12
Voxel size (mm)	0.2 (minimum)	0.16	0.4 / 0.2	n/a

Computed tomography (CT) is an essential technique in a modern medical radiology department. Very often, the CT examination is the first and remains the only diagnostic imaging procedure needed. Despite the recent developments and commercial availability of digital systems plain film and panoramic radiography remains the standard in clinical practice for dental and maxillofacial imaging. In contrast, medical CT imaging has grown at an estimated annual rate of 15-20%, primarily due to its recognized benefits and disposability. Computed tomography is one of the most valuable diagnostic tools in medicine and its popularity has increased markedly. While in 1983

approximately 5 million CT examinations were undertaken in the United States, the number increased to 20 million in 1995. This is a 400% increase over twelve years. In the year 1991, CT examinations comprised 2% of all radiographic examinations and in 2001 this percentage has risen to 10-15% of the total. (International Commission on Radiological Protection 2001). Computer tomography has advanced each decade since its introduction in the mid-1970s, mostly as a result of improvements in hardware that express themselves in higher speed and better image quality. In the 1990s, spiral/helical CT became the *de facto* standard instrument in the medical field, and since its introduction in 1998, multislice CT (also known as multirow detector CT) has revolutionized this field (Marsh and Vannier 1983). Medical CT scanning has been used for craniofacial imaging since its inception, but did not become popular until scanners with higher resolution and a slice thicknesses of 2 mm were developed in the early 1980s (Mozzo et al. 1998). Due to the high levels of radiation that are generated with early generations of CT the use was limited only to certain cases in which the risk-benefit ratio seemed favorable like in cancer or trauma patients. Suitable craniofacial

cone-beam CT scanners were developed in the late 1990s and became commercially available soon thereafter. In 2001, the Food and Drug Administration (FDA) approved the first of these for sale in the USA, and several additional manufacturers have systems in various stages of development and testing. These cone-beam scanners are intrinsically three-dimensional (3-D) in their acquisition of images, and offer usable images from systems that are sufficiently compact and inexpensive to be installed in clinics and private dental, oral surgery, or orthodontic practices (Vannier 2003). With the development of these special low dose craniofacial cone beam CT scanners the actual era of three dimensional digital imaging in dentistry began.

In multi-slice CT scanners, the source of radiation is a high output rotation anode generator which generates a fan shaped beam that rotates around the patient's head multiple times. The data is recorded on solid-state image detectors which are arranged in a 360° setting around the patient and then mathematically reassembled and formatted into diagnostic images. These apparatuses can be classified as 4, 8, 12, 16, 32, and 64-slice machines; one slice being one 360° rotation around the patient. The

generated slices are parallel. Therefore, there is a small gap between each slice. To provide a continuous image, these gaps are filled by mathematical extrapolation that is based on averages. For this reason, the accumulated gaps separating each slice cause a system inherent error in medical CT scans (Winter et al. 2005). Traditional dental radiographs are two dimensional representations of three dimensional structures in which all layers are superimposed. In contrast, multislice CT generates images of significantly improved contrast at the cost of reduced spatial resolution (Michael 2001). A multitude of CT applications in dentistry have been described which range from implant placement to airway studies (Schwarz et al 1987; Abrahams 1993; Miles, Van Dis 1993; Frederiksen 1995).

In cone beam computed tomography (CBCT), the x-ray source is a low-energy anode tube, which is similar to the x-ray source in a dental panoramic unit. The tube-detector system performs a complete 360° rotation around the head of the patient, during which a series of exposures (typically, one for each degree) is taken. These digital images comprise the two dimensional raw data used by the reconstruction software to generate the

volume image. The reconstruction volume is either a cylinder or a sphere depending on the size and shape of the radiographic detector. Digital radiograms are acquired in a 512 x 512 format with a scan rate of 30 frames per second (FPS). The CBCT technique allows, in principle, obtainment of data acquisitions much faster than traditional CT. With the new machines the speed is limited by technological and economical factors. Presently, the scan time is 12 s (360 frames/30 FPS). The system, moreover, is particularly advantageous in using X-ray emission. In fact, in fan-beam techniques only a few thousandths (on average) of the produced beam is employed in producing images, and in the case of volumetric reconstruction it is necessary to produce n-times the X-photons used by CBCT (if n is the number of slices necessary to cover the volume of interest). Low radiological power and low mechanical requirements, due to low scan speed, determine the manufacturing simplicity and low price of the new machine. There is also a device to control the size of the beam and to limit the irradiated volume. Problems due to limited dynamic range of the detector are overcome by using a special wedge-shaped circular filter which modulates properly the

intensity of the incident beam, reducing the intensity on the borders with respect to the center, according to the approximately circular cross section of the head of the patient, thus reducing the dynamics of the transmitted beam. Scattered radiation limits the signal-to-noise ratio (SNR), but the air gap between object and detector (30 cm long) is sufficient to obtain good improvement in SNR; moreover, low-contrast resolution is not the main objective of the machine. The raw data are preliminarily corrected for geometrical and dynamic distortions of the detector and are then elaborated by a modified version of the 3D filtered back-projection method proposed by Feldkamp et al (Feldkamp et al. 1984). This Feldkamp algorithm is used to reconstruct a 3-dimensional image at about 130,000,000 isotropic voxels (512x512x512 pixels) data (Mozzo et al. 1998; Dus 2002; Seo et al. 2003; Yamamoto et al. 2003;) Also, as a result of the different beam geometry, no gaps are created in the scanning process. A cone shaped beam is utilized for data acquisition thus creating overlapping continuous volumes (Winter et al. 2005).

In 1982, the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA)

formed a committee to develop standards for the interconnection of digital imaging devices. Version 1.0 of the standard, published in 1985, specifies a hardware interface supporting point-to-point (not network) image transmission, a data dictionary (a set of rules for encoding information), and a set of commands to initiate transactions. Version 2.0, published in 1988, also addresses point-to-point image transmission and provides semantic rules by which messages (streams of bits representing information in transit from one device to another) are organized. Version 3.0, also referred to as DICOM (Digital Imaging and Communications in Medicine), was finalized in 1992. The DICOM standard encourages open systems interconnection of imaging equipment over standard networks, while maintaining compatibility with earlier point-to-point connection standards. The DICOM standard conforms fully with the International Standards Organization reference model for network communications (ISORM), addresses the issue of conformance, and incorporates the concept of object-oriented design (Bidgewood, Horii 1992).

Although the levels of radiation used in dentistry are generally fairly low compared to other areas of

medicine, all existing radiological policies are based on the assumption, that some risk to the patient does exist nonetheless, and that this risk must be clearly outweighed by the benefits (White 1992). The new available dental imaging technologies, while clearly providing a wealth of additional information, must be examined for the amount of patient risk, i.e., radiation, involved with data acquisition, in order to become a routine diagnostic aid. An example for this is the use of conventional medical helical computer tomographs in the field of dentistry, for example implant placement. Data acquisition with this technique results in doses that are thousands of times greater than those required for plain film radiography (Scaf et al. 1997). Nevertheless, medical CT scans have been reportedly used for implant placement (Benjamin 1987; Weinberg 1993; Cavalcanti et al. 2002). Certainly, this technique was not used on a routine basis, but it provided a substantial aid in difficult cases were the clinician deemed it necessary (Santler et al. 1998).

After its introduction to the field of dentistry, similar studies have been and are still being conducted with Cone Beam Computed Tomographs for many questions to

date remain unanswered. According to Mah et al. (2003), the average effective tissue dose is approximately 50.0 μSv in the NewTom™ 9000 unit. This is a dose equivalent to roughly one full mouth series of periapical radiographs. This amount of radiation is close to five scans with a conventional panoramic dental radiograph. A medical CT scanner would generate 40 to 60 times the amount of radiation. Therefore it can be said that by utilizing the CBCT technology instead of a conventional medical CT scan, the clinician can influence the patient's risk-benefit ratio positively by reducing the amount of radiation while still being able to gather at least the same amount of information. It also seems like the additional information gained with a cone beam 3-D scan as opposed to using a plain film radiograph may outweigh the additional radiation exposure to the patient and thus not altering the risk-benefit ratio significantly. Ludlow et al. (2003) also support the finding that craniofacial three dimensional imaging is now possible at significantly reduced radiation levels with their study. However they found that the radiation dose is three to seven times greater than in a panoramic radiograph. This would be equivalent to 1% or 3.5 days of

the annual per capital background radiation dose in the USA. They agreed that, in their study cone beam computed tomography compared favorably to plain film radiography and that, in the field of maxillofacial imaging, CBCT technology was superior to medical CT scans. The reported differences in radiation levels can be attributed to different scanner settings, differences in the detectors used and differences in the study protocol, which makes it difficult to compare studies directly to one another. Nevertheless all studies agree on the fact that the extremely reduced radiation levels of the dental cone beam CT units compared to the earlier generation CT units and the increased information they deliver produce an advantageous risk-benefit ratio for the patient and thus representing a valid imaging alternative to plain film radiography.

Other advantages are a great improvement in data acquisition efficiency, grayscale resolution and spatial resolution uniformity, substantially better utilization of x-ray photons generated by the x-ray tube compared to a fan beam CT, and significant advancement in clinical three-dimensional CT applications and a great reduction in costs (Ning et al. 2003). Jaffray and Siewerdsen

(2000) noted the following:

> "the CBCT approach offers two important features that dramatically reduce its cost in comparison to a conventional scanner. First, the cone beam nature of the acquisition does not require an additional mechanism to move the patient during the acquisition. Second, the use of a cone beam, as opposed to a fan beam, significantly increases the X-ray utilization, lowering the X-ray tube heat capacity required for volumetric scanning. For the same source and detector geometry, the efficiency roughly scales with slice thickness. For example, the X-ray utilization increases by a factor of 30 in going from a 3 mm slice in a conventional scanner to a cone angle corresponding to a 100 mm slice with a cone beam system. This would reduce heat load capacity dramatically. From our experience, a 5200 KHU X-ray tube costs approximately $70,000, whereas a 600 KHU X-ray tube (a factor of ~10 lower in capacity) costs roughly $6000."

Sophisticated software is available for every unit allowing image processing and measuring. Recently, many articles on Cone Beam CT use and benefits have been published. The link between the facial growth and airway function has been a subject of controversy in orthodontics for many years. A question, that research was not able to answer to date with the available methods. Aboudara et al. have used the cone beam CT technology for volumetric imaging of patient's airways. They compared this data to data obtained from conventional lateral cephalometric imaging. Due to a too

small sample their results did not have enough power, but they came to the conclusion that there may be airway information that is not accurately depicted on the lateral headfilm. More analysis with a larger sample size will be needed to obtain valid information (Aboudara et al 2003). Still, this shows another promissing area of CBCT application. A closely related area of investigation is obstructive sleep apnea syndrome (OSAS). OSAS has some correlation to airway volume and anatomy. Using CBCT for this application may reveal interesting information. This possibility has been explored already, but to date, available sample sizes are too small to draw valid conclusions (Ogawa et al. 2005) Kitai et al. reported a rare case in which a 15 year old male presented with multiple impacted and supernumerary teeth. Plain film radiography proved to be undiagnostic due to severe overlap of multiple layers. CBCT technology was used to properly diagnose and treatment plan the case (Kitai et al. 2003). Moore (2005) advocated CBCT as a new tool for esthetic implant planning. In dental implant planning, bone quality and density plays an important role. These parameters are routinely assessed subjectively for conventional methods of gaining objective information are

invasive. With cone beam CT a new method of assessing bone quality objectively has been developed (Aranyarachkul et al. 2005). Applications for cone beam 3-D imaging in orthodontics are plentifold (Kau et al. 2005). Also, the dentoskelettal effects of orthodontic treatment can be assessed with this new imaging technique (Garib et al. 2005). With very versatile range of application in the dental specialties CBCT has already become an invaluable tool in diagnosis and treatment planning. Because, it is a new technology, one can expect to see more publications on new applications and benefits in the very near future.

To date the use of cone CBCT scans is still somewhat limited and the full benefits are most likely not exploited. Cone beam computed tomography generated images contain a wealth of information; more information in fact than can be used at this point. Danforth stated, that his view for the near future is the development of the three dimensional patient model. An "anatomically accurate "virtual patient" upon which diagnosis, simulation, and treatment planning" can occur (Danforth 2003). So, with time it may be possible that a CBCT scanner will become the standard of care and a cornerstone of the modern

dental practice. The specialty of orthodontics already experiences benefits from the use of cone beam Computed Tomography (Kau 2005), with more still to come. It may be the specialty that benefits most from the introduction of CBCT to dentistry for it can accommodate most of its diagnostic needs: soft and hard tissue imaging, views from every angle, image processing and measuring software make for a useful technique that may change the face of orthodontic research and practice. Soon, it may be possible to acquire all the information one needs to properly diagnose an orthodontic case from one single CBCT scan, treatment plan it, and perhaps simulate tooth movement and even demonstrate a prediction of the final result. The ideal situation for optimal orthodontic diagnosis and treatment planning would be a complete three dimensional craniofacial record in digital format. Grossly, the technical requirements already exist. The available Cone Beam Computerized Tomography shoes some potential of developing into the single source of such record (Palomo and Hans).

So far in orthodontics, CBCT generated images have mostly been used to gather qualitative information. In order to maximize the amount of diagnostic information

that can be obtained from a volumetric scan it would be desirable and necessary to also generate quantitative information. Linear and angular measurements can be performed on volumetric images with the appropriate software; only the accuracy of such measurements has not been researched sufficiently. In the era of evidence based dentistry, clinical decisions based on these measurements can not be justified unless proven accurate and reproducible. Therefore there clearly is the need for more studies in this field.

Only two studies have been conducted so far to compare measurements generated from a CBCT scan with actual measurements on a skull. In the first study, the NewTom™ 3G unit was used to scan dry skulls and compare linear measurements on the scan with the actual dimensions of the skull. The results showed that the measurements on the skulls were always larger than those for the CBCT images, but these differences were only statistically significant for measurements of the internal structures of the cranial base (Lascala et al. 2004). In the second study, skulls were scanned with the the i-CAT™ CBCT unit. These scans were compared with the anatomic truth and to different plainfilm radiographic

images. Except for very few outliers, the three dimensional radiographic reconstructions provided accurate and reliable linear measurements (Hilgers et al. 2005).

Although dentitions have been scanned multiple times, never has the attempt been made to compare dental arch measurements of scanned jaws with measurements of the anatomic truth - the actual teeth. Since it is possible to separate the teeth apart and also segment them from bone, three dimensional dental volumes can be created from a CBCT scan on which it is technically possible to perform dental arch measurements. No studies so far have investigated the accuracy of linear dental measurements generated on CBCT scans compared with the true anatomic dimensions.

THE RELIABILITY AND ACCURACY OF DENTAL ARCH MEASUREMENTS ON THREE DIMENSIONAL CONE BEAM COMPUTED TOMOGRAPHY SCANS

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ABSTRACT:

Introduction: Orthodontic study models are an integral part of the orthodontic records necessary for proper diagnosis and treatment planning. This study investigated the reliability and accuracy of dental measurements generated from cone beam computed tomography (CBCT) reconstructions.

Materials and Methods: Thirty human skulls were scanned with a dental CBCT and three dimensional reconstructions of the dentition were generated. Ten measurements (overbite, overjet, maxillary and mandibular measure for intermolar width, intercanine width, arch length available, and arch length required) were carried out directly on the dentition of the skulls with a high precision digital caliper and on the digital reconstructions using commercially available software. Reliability and accuracy were assessed using intra-class correlation and paired Student's t-test. A p-value $p \leq 0.05$ was used to assign statistical significance.

Results: Preliminary data analysis identified a systematic software error that subtracted 0.28 mm from each measurement. After correction for this error, both the CBCT measures and caliper measures were highly reliable ($r > 0.90$). Intra-class correlations between CBCT and callipers ranged from 0.76 to 0.99 and no statistically significant differences were detected for any of the ten measures.

Conclusions: The commercially available software program used in this study to calculate linear measures on CBCT reconstructions incorporates a small but significant systematic error. After adjustment for this error, measurements on CBCT scans were as accurate and reliable as measurements made directly on the dentition.

Introduction

Orthodontic study models are an important part of the treatment planning process.[1,2] According to Proffit et al., a study model is a precise three dimensional replica of a patient's dentition on which certain measurements can be performed easier and more accurately than in the patient's mouth. With the increasing use of computers in the orthodontic office over the past twenty five years a greater number of digital multimedia applications have become available to the clinician and his staff to facilitate standard procedures in practice and management - the final goal being the fully digital orthodontic office.[3,4] Methods have been developed to create digital study models including laser scanning of plaster casts,[6] intraoral laser scanning,[7] non-destructive scanning of plaster casts or impressions with micro computer tomographs and destructive imaging of plaster casts with incremental image captures.[8]

The application of 3D virtual study models in the orthodontic practice setting has great advantages over the use of conventional plaster models. They are stored electronically and thus consume virtual space instead of the physical space required to store plaster models which comes with financial and logistic burdens for the orthodontist.[9] Model retrieval is greatly facilitated, communication with other dental specialties is improved, and the traditional duplicating of plaster casts, handling and shipping has become obsolete.

Several companies now offer virtual study models.[10-12] Proprietary software for virtual model analysis is provided by the companies, giving the clinician valuable tools for almost any desirable application[13]. The ability of 3D virtual models to

represent the patient's dentition accurately has been investigated and the validity and reproducibility of measurements on these models has been extensively studied. The accuracy proved to be sufficient for clinical use, but inferior to the measurements obtained from plaster casts and digital callipers which therefore should be preferred for scientific work.[13-15]

Being less time consuming, easy to use, and very cost effective at comparable levels of clinical accuracy, a strong argument can be made for the routine application of computer based three dimensional models.[16] In the year 2004, approximately 10% of all orthodontists in Canada and the United States were utilizing digital models and this popularity is constantly increasing.[17]

Despite all the advantages of virtual models, some time consuming and costly steps are still necessary to generate them. The application of three dimensional volumetric scans using CBCT may offer a solution here.

Computed tomography is one of the most valuable diagnostic tools in medicine and its popularity has increased markedly. While in 1983 circa 5 million CT examinations were undertaken in the United States, the number increased to 20 million in 1995. This is a 400% increase over twelve years. In the year 1991, CT examinations comprised 2% of all radiographic examinations and in 2001 this percentage has risen to 10-15% of the total.[18] Medical CT scanning has been used for craniofacial imaging since its inception, but did not become popular until scanners with higher resolution and a slice thicknesses of 2 mm were developed in the early

1980s.[19] Suitable craniofacial cone beam CT scanners were developed in the late 1990s and became commercially available soon thereafter. These cone beam scanners are three-dimensional (3D) in their acquisition of images, and offer usable images from systems that are sufficiently compact and inexpensive to be installed in clinics and private dental, oral surgery, or orthodontic practices.[20] With the development of these special low dose craniofacial cone beam CT scanners the actual era of three dimensional digital imaging in dentistry began.

A multitude of CT applications in dentistry have been described which range from implant placement to airway studies.[21-24] The CBCT technique allows a more rapid data acquisitions than traditional CT. Sophisticated software is available for every unit allowing image processing and measuring. Recently, many articles on CBCT use and benefits have been published.[24-30] With a very versatile range of application in the dental specialties CBCT is becoming a valuable aid for diagnosis and treatment planning. Because, it is a new technology, one can expect to see more publications on new applications and benefits in the very near future. The specialty of orthodontics already experiences benefits from the use of cone beam Computed Tomography, with more still to come.[30] The ideal situation for optimal orthodontic diagnosis and treatment planning would be a complete three dimensional craniofacial record in digital format. Grossly, the technical requirements already exist. The available Cone Beam Computerized Tomography shows some potential of developing into the single source of such record.[31]

So far in orthodontics, CBCT generated images have predominately been used

to gather qualitative information. In order to maximize the amount of diagnostic information that can be obtained from a volumetric scan it would be desirable and necessary to also generate quantitative information.

To date only two studies have been conducted to compare measurements generated from a CBCT scan with actual measurements on a skull. In the first study, the NewTom 3G™ unit was used to scan dry skulls and compare linear measurements on the scan with the actual dimensions of the skull. The results showed that the measurements on the skulls were always larger than those for the CBCT images, but these differences were only statistically significant for measurements of the internal structures of the cranial base.[32] In the second study, skulls were scanned with the the i-CAT™ CBCT unit. These scans were compared with the anatomic truth and to different plain-film radiographic images. Except for very few outliers, the three dimensional radiographic reconstructions provided accurate and reliable linear measurements.[33]

Although dentitions have been scanned multiple times, never has the attempt been made to compare dental arch measurements of scanned jaws with measurements of the anatomic truth: the actual teeth. Since it is possible to separate the teeth apart and also segment them from bone, three dimensional dental volumes can be created from a CBCT scan on which it is technically possible to perform dental arch measurements. No studies so far have investigated the accuracy of linear dental measurements generated on CBCT scans compared with the true anatomic dimensions.

Materials and Methods

Sample:

The sample consisted of thirty skulls from the Hamman-Todd Collection, at the Bolton-Brush Growth Study Center and the Museum of Natural History, Cleveland, OH. All skulls had intact maxillary and mandibular jaws and sufficient teeth to ensure a stable and reproducible occlusion .

Creation of images:

The skulls were scanned and imaged with the Hitachi CB Mercuray^{TM} Volumetic Digital Imaging Unit (Hitachi Medical Systems America, Inc., Twinsburg, OH) using 100 kVp, and 10 mA with a final voxel size of 0.28mm. The skulls were imaged in maximum intercuspation and volumetric images were reconstructed according to the manufacturers specifications. Using the computer program CB Works^{TM}2.0 (CyberMed, Inc., Seoul, Korea) in the setting "Volume Operation" with the function "Sculpt" the maxilla and the mandible were manually segmented from the entire volume to generate three separate volumes. One containing the maxilla and maxillary dentition, one containing the mandible and mandibular dentition (Fig.1 and 2) and one containing both the maxilla and and mandible with the teeth in maximum intercuspation (Fig.3,4,5).

Data collection:

The following measurements were carried out directly on the skulls, and on

the digital volumetric images:

- Overjet: Measured as the distance between the labial surface of the right maxillary incisor at the incisal edge level and the labial surface of the right mandibular incisor parallel to the occlusal plane. If either of the two incisors were missing, the measurement was carried out on the incisors of the contra-lateral side.
- Overbite: measured as the vertical overlap of the right maxillary incisor and the right mandibular incisor perpendicular to the occlusal plane. If either of the two incisors were missing, the incisors of the contralateral side were used.
- Mesiodistal widths: As described by Hunter and Priest[34] the greatest mesiodistal diameter from the mesial anatomic contact point to the distal anatomic contact point of each tooth is measured parallel to the occlusal plane. Measurements are recorded to the nearest 0.1 mm.
- Arch length: The arch length was measured by the segment arch approach in which a dental arch is subdivided into four segments A-D. Segment A is the distance from the mesial contact point of the right first permanent molar to the mesial contact point of the right canine. Segment B is the distance from the mesial contact point of the right canine to the mesial contact point of the right central incisor. Segment C is the distance from the mesial contact point of the right central incisor to the mesial contact point of the left canine. Segment D is the distance from the mesial contact point of the left canine to the mesial contact point of the left first permanent molar. The segments were summed to the nearest 0.1 mm to obtain the arch length for both the maxillary and

mandibular arches which indicates the space available for alignment of all the teeth.

- Arch width: Intermolar width was measured as the distance between the mesiolingual cusp tips of the permanent maxillary first molars and between the central grooves of mandibular first molars. If a first molar was missing, the equivalent measurement was carried out on the permanent second molars. Intercanine width was measured as the distance between the crown tips of the permanent canines. In case of a missing canine, the distance between the buccal cusp tips of the first premolars was measured. Measurements were recorded to the nearest 0.1 mm.
- Space available is the summation of the maxillary and mandibular arch length segments (A + B + C + D) to the nearest 0.1 mm and equals the arch length.
- Space required is the summation of the maxillary and mandibular mesiodistal tooth widths including right and left second premolar, first premolar, canine, lateral incisor, and central incisor. This measurement was carried out both directly on the teeth of the jaws and on the computer-based models.

Measurement technique:

Measurements directly on the skulls were made using a high precision digital caliper calibrated to the nearest 0.01 mm (Digimatic Caliper™: Code No.: 500-171-

20 Model No.: CD-6''CX, Mitutoyo America Corp, Plymouth, Mich).

Measurements on the scans were made using the computer program CB Works^{TM}2.0. In the setting "Volume Operation" the function "Measure Length" was used to measure distances on the three dimensional volumes. After marking two points on the object of interest, the computer calculated the shortest distance between these points and indicated them to the nearest 0.1 mm. Data was entered into a Microsoft Office Excel 2003^{TM} Spreadsheet (Microsoft Corp., Redmond, WA). using a USB Input Device^{TM} (USB Input Device^{TM}, Code No.: 264-01-10, Model No.: IT-012U, Mitutoyo America Corp, Plymouth, Mich) for caliper measurements and manually for measurements from CB Works^{TM}2.0.

Statistical analysis:

Intra-operator reliability for each method was estimated using the intra-class correlation coefficient. All ten measures were repeated on twelve skulls. The repeat measures were done a minimum of one week apart.

The accuracy of the computer generated measurements was assessed by comparing these measurements to the anatomical truth i.e. direct measures made on the skull using digital calipers. Paired Student's t-test with Bonferroni Correction was used to determine statistically significant differences between the two groups. The level of significance was set at $p \leq 0.05$. Intra-class correlation coefficients were used to determine how well the two methods are correlated.

All calculations were executed using the computer program Statistical Package for

the Social Sciences: SPSS^{TM}14.0 (SPSS Inc. Chicago, Il).

Preliminary data analysis revealed normal distribution for both samples and indicated a systematic error of the magnitude of 0.28mm (the size of a single voxel) for every measurement. The source of this systematic software error is depicted diagramatically in figure 6. The measurements on the digital volumes were adjusted for this error and are reported in the results section.

Results

Reliability:

The intra-operator reliability for all ten parameters that were measured with both methods, digital callipers on the dentition directly and with software on the CBCT scans was analysed. Table I illustrates the intra-class correlation coefficients, which were above 0.95 for all digital calliper and CBCT measurements alike. Both methods therefore prove to be highly reliable (Table I).

Accuracy:

The accuracy of the new method, measuring dental arch dimensions on CBCT scans, was analyzed. The level of significance was set at $p \leq 0.05$ and the results were adjusted with Bonferroni correction.

After adjustment for the systematic error, data analysis revealed no statistically significant difference between the methods and a high correlation (Table II).

Discussion:

The goal of the present study was to assess the reliability and accuracy of dental measurements made on CBCT images. The same measurements were carried out on the teeth of skulls with high precision digital callipers and used as the gold standard for comparison.

Both methods were very reliable with correlations between 0.96 and 0.99. This finding compares favorably with results reported by other investigators using digital calipers.[13,15] Of the two studies that previously assessed the accuracy of measurements on CBCT scans, one did not evaluate the reliability of the measurement methods.[32] The other used the standard deviations to estimate intra-operator reliability and concluded that it was high for CBCT measurements.[33] Although this is the first study to use intra-class correlation as a measure of reliability for CBCT measurements the results are consistant with previous work and suggest that the software programs available to measure linear distances from CBCT images are reliable.

Although reliable, preliminary data analysis showed a tendency for the measurements generated on the virtual volumes to be slightly smaller than the gold standard. The consistency of the difference suggested a systematic error in the CBCT measurement method. Because of the complexity of computed tomography, a systematic error could be introduced at several levels. Our investigation revealed that this error was evoked by the measurement software (Fig. 6). While the caliper measured the distance between the mesial and distal height of contour of the actual tooth (x), the software measured the distance between the mesial most and distal most

voxel of the volumetric image of the tooth. Because a voxel is a volume the software had to define a precise point within this volume from which to measure. This point was the center of the voxel (M). In other words, the software actually measured the distance between the midpoints of the voxels (y). For the field of view used in this study, the voxel size was 0.28 mm. When measurements were made from the center of the voxel, one half of the voxel was not included in the measurement on either side. This lead to CBCT measurements that were 0.28 mm smaller than caliper measurements. Since the error was less than half a millimeter, it may not be significant for large structures. However, teeth are relatively small and when multiple small measures are summed, as was done in the space analysis, this small difference becomes significant. Because the source and the magnitude of the error were identified it was possible to adjust the values measured on the CBCT images to correct for this error. After correction, all measurements made on the CBCT images were as accurate as the gold standard.

The uncorrected values found in this study are similar to the findings of Lascala et al. who showed that CBCT measurements for internal and external cranial anatomical sites had a tendency to be slightly smaller than the same measurements carried out with calipers directly on the skulls.[32] No explanation for this was given for this finding but since the values were consistently smaller it is likely that the same sort of systematic error occurred in this previous study. Likewise, Hilgers et al. found no statistical difference between the measurements from the CBCT images and the anatomical truth.[33] Again, because similar software was employed, a similar error might have been present. However, these investigators were measuring anatomic

structures such as the head of the mandibular condyle which is considerable larger than a single tooth. For larger structures, small systematic errors such as the one detected in the present study, will not be clinically or statistically significant.

Conclusion

The results of present study support the use of three dimensional reconstructions of the dentition from CBCT for orthodontic diagnosis and treatment planning However, the measurement software employed underestimates the values measured on the virtual volumes by the size of a voxel due to a systematic error that affects accuracy. This error can be corrected by adding the width of one voxel to each linear measure. After this correction, measurements made on CBCT images are both reliable and accurate.

References:

1. Han KU, Vig KWL, Weintraub JA, Vig PS, Kowalski CJ. Consistency of orthodontic treatment decisions relative to diagnostic records. Am J Orthod Dentofacial Orthop. 1991; 100(3):212-219

2. Naccache H, Bernard C, Brodeur JM, Pournier A. Epidemiological evaluation of a computerized diagnosis in orthodontics. *J Dent Res.* 1989;68:776

3. McDavid WD, Dove SB, Welander U, Tronje G. Direct digital extraoral radiography of the head and neck with a solid-state linear x-ray detector. Oral Surg, Oral Med, Oral Path. 1992 Dec;74(6):811-817.

4. Scholz RP. Considerations in selecting a digital camera for orthodontic records. Am J Orthod Dentofacial Orthop. 1998 Nov;114(5):603-5.

6. Motohashi N, Kuroda T. A 3D computer-aided design system applied to diagnosis and treatment planning in orthodontics and orthognathic surgery. Eur J Orthod. 1999; 21:263–274

7. Commer P, Bourauel C, Maier K, Jager A. Construction and testing of a computer-based intraoral laser scanner for determining tooth positions. Med Eng Phys. 2000; 22:625–635.

8. Mah JK, Hatcher D. Current status and future needs in craniofacial imaging. Orthod Craniofacial Res, 2003;6 suppl. 1:10-16

9. Bell A, Ayoub AF, Siebert P. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. J Orthod. 2003;30 (3):219-23.

10. Orthocad. www.orthocad.com. Accessed June 2006

11. Geodigm. www.geodigm.com. Accessed June 2006

12. Invisalign. www.invisalign.com. Accessed June 2006

13. Quimby ML, Vig KWL, Rashid RG, Firestone AR. The accuracy and reliability of measurements made on computer-Based digital models. Angle Orthod. 2004;74:298-303.

14. Tomassetti JJ, Taloumis LJ, Denny JM, Fischer JR Jr. A comparison of 3 computerized bolton tooth-size analyses with a commonly used method. Angle Orthod. 2001; 71:351–357.

15. Zilberman O, Huggare JAV, Parikakis KA. Evaluation of the Validity of Tooth

Size and Arch Width Measurements Using Conventional and Three-dimensional Virtual Orthodontic Models. Angle Orthod. 2003;73:301-306.

16. Garino F, Garino, GB. Comparison of dental arch measurements between stone and digital dental casts. World J Orthod. 2002;3:250-254

17. Joffe L. OrthoCad: digital models for a digital era. British Journal of Orthodontics 2004 Dec; 31 (4):344-347.

18. International Commission on Radiological Protection. Publication 87. Managing Patient Dose in Computed Tomography. Oxford: Pergamon Press. Annals of the ICRP Vol. 30/4, 2001

19. Mozzo P et al, A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. EurRadiol 8:1558-64, 1998

20. Vannier MW. Craniofacial computed tomography scanning: technology, applications and future trends. Orthod Craniofacial Res. 6 (Suppl. 1) 2003;23-30.

21. Schwarz MS, Rothman SLG, Rhodes ML, Chafetz N. Computed tomography: Part I. Preoperative assessment of the mandible for endosseous implant surgery. Int J Oral Maxillofac Implants. 1987;2:137-48.

22. Miles DA, Van Dis ML. Implant radiology. DCNA 1993;37;645-668.

23. Frederiksen NL. Diagnostic imaging in dental implantology. Oral Surg, Oral Med, Oral Path. 1995;80:540-554.

24. Aboudara CA, Hatcher D, Nielsen IL, Miller A. A three-dimensional evaluation of the upper airway in adolescents. Orthod Craniofac Res. 2003;6 Suppl 1:173-5.

25. Ogawa T, Enciso R, Memon A, Mah JK, Clark GT. Evaluation of 3D airway imaging of obstructive sleep apnea with cone-beam computed tomography. Stud Health Technol Inform. 2005;111:365-368.

26. Kitai N, Fujii Y, Murakami S, Takada K. Three-dimensional evaluation of a rare case with multiple impacted teeth using CT. J Clin Pediatr Dent. 2003;27(2):117-21.

27. Moore WS. Cone beam CT: a new tool for esthetic implant planning. Tex Dent J. 2005 Apr;122(4):334-40.

28. Aranyarachkul P, Caruso J, Gantes B, Schulz E, Riggs M, Dus I, Yamada JM, Criger M. Bone density asessments of dental implant sites: 2. Quantitative cone-beam computerized tomography. Int J Oral Maxillofac Implants. 2005;20(3)416-24.

29. Garib DG, Henriques JF, Janson G, Freitas MR, Coelho RA. Rapid maxillary expansion--tooth tissue-borne versus tooth-borne expanders: a computed tomography evaluation of dentoskeletal effects. Angle Orthod. 2005 Jul;75(4):548-57.

30. Kau CH, Palomo JM, Hans MG. Three-Dimensional Cone Beam Computerized Tomography in Orthodontics. J Orthod. 2005 Dec;32(4):282-93.

31. Palomo JM and Hans MG. Three-Dimensional Craniofacial Imaging in Orthodontics. J Med Sci; in press.

32. Lascala CA, Panella J, Marques MM. Analysis of the accuracy of linear measurements obtained by cone beam computed tomography (CBCT-NewTom). Dentomaxillofac. Radiol. 2004 Sep;33(5):291-4.

33. Hilgers ML, Scarfe WC, Scheetz JP, Farman AG. Accuracy of linerar temporomandibular joint measurements with cone beam computed tomography and digital cephalometric rediography. Am J Orthod Dentofacial Orthop. 2005; 128:803-11)

34. Hunter WS, Priest WR. Errors and discrepancy in measurement of tooth sizes. J Dent Res. 1960;39:405–414.

Fig.1-occlusal aspect of maxillary virtual model

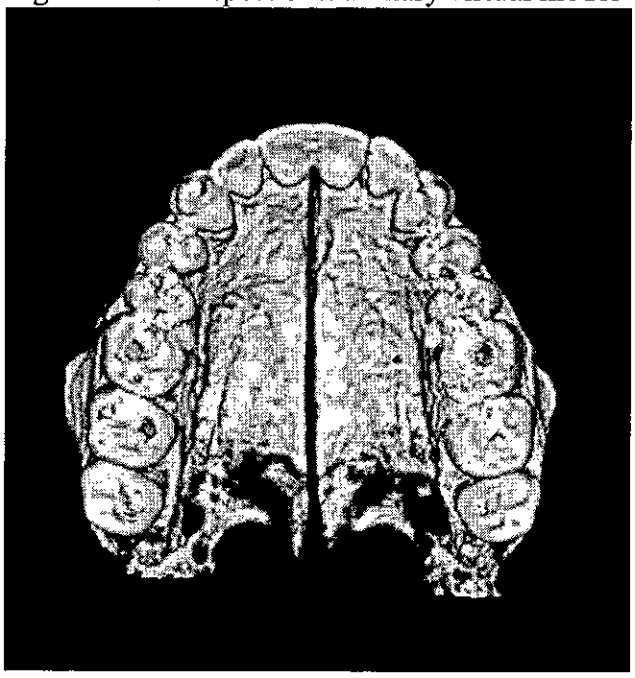


Fig.2-occlusal aspect of mandibular virtual model

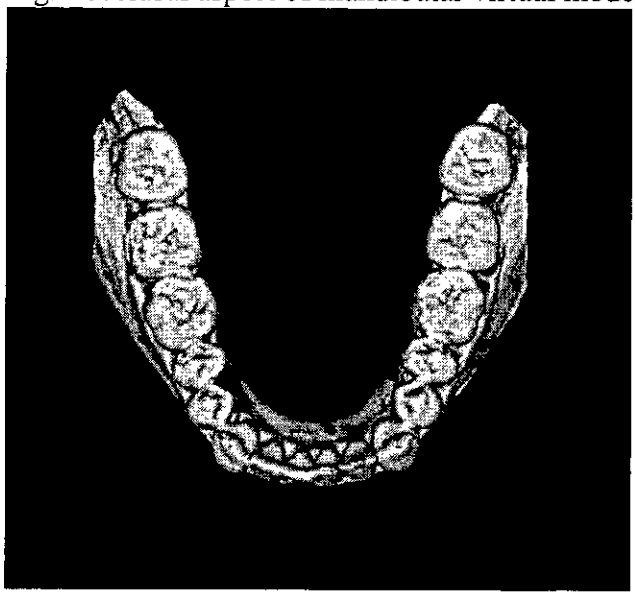


Fig.3-frontal aspect of virtual model

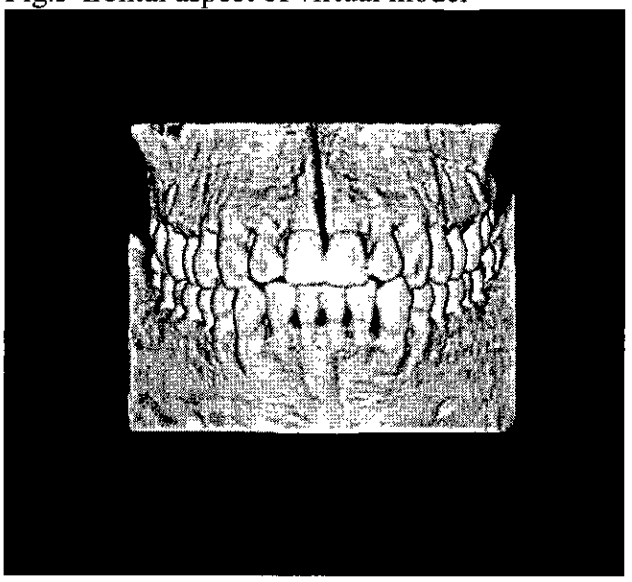


Fig 4.-Lateral aspect of virtual model (left side)

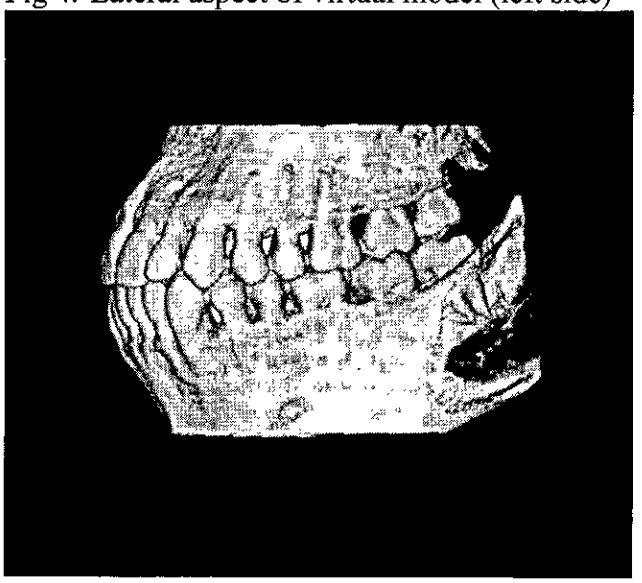


Fig.5-lateral aspect of virtual model (right side)

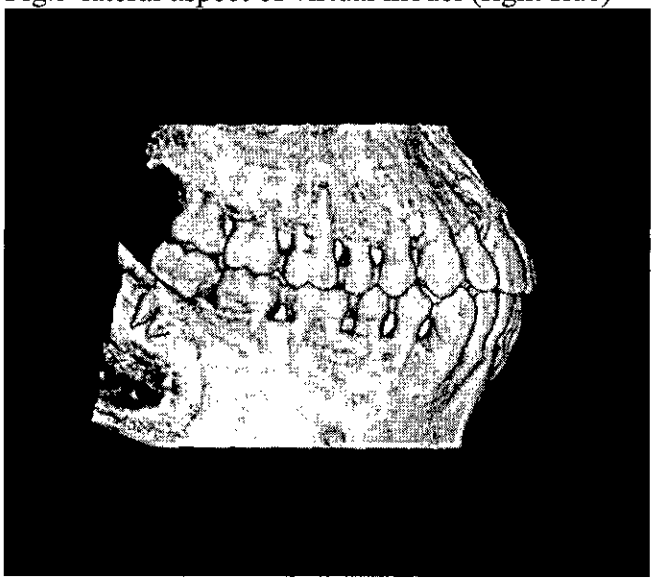


Fig.6-diagrammatic illustration of systematic error

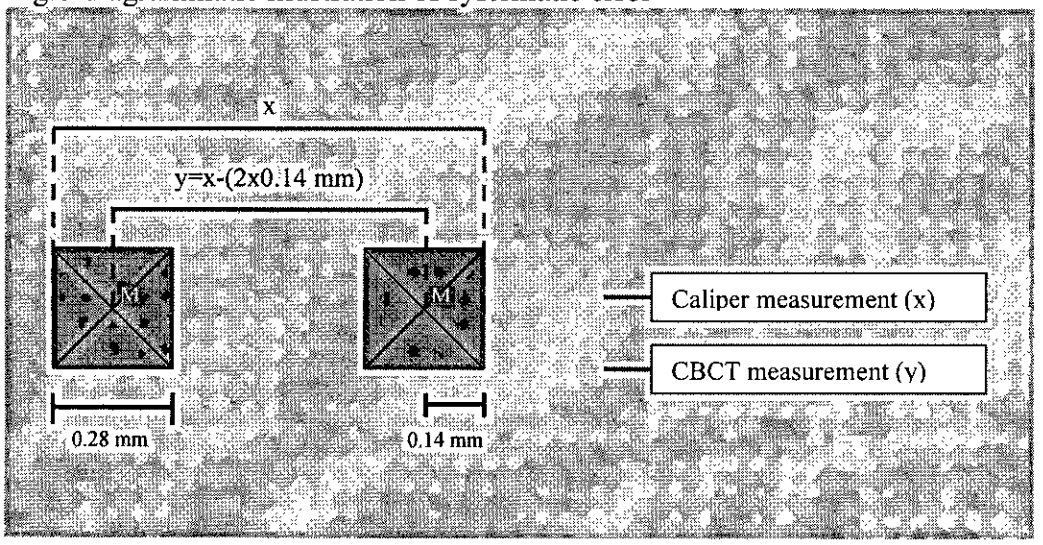


Table I-Intra-operator reliability for digital caliper (DC) and cone beam computed tomography (CBCT measurements) (n=12)

	DC	CBCT
Measurement	r	r
Overjet	0.995	0.993
Overbite	0.999	0.998
Maxillary intercanine width	0.999	0.994
Mandibular intercanine width	0.995	0.994
Maxillary intermolar width	0.997	0.956
Mandibular intermolar width	0.998	0.989
Maxillary space available	0.995	0.995
Mandibular space available	0.997	0.996
Maxillary space required	0.999	0.998
Mandibular space required	0.996	0.991

Table II-Mean, standard deviation, and correlation between digital caliper (DC) measurements and CBCT measurements after calibration(n=30)

	DC		CBCT					
Measurement	Mean	SD	Mean	SD	Δ Mean	Δ SD	r	Sig.
Overjet	1.8	2.6	2.1	2.7	-0.4	1.0	0.931	n/s
Overbite	0.49	3.36	0.56	3.55	-0.07	1.02	0.958	n/s
Maxillary intercanine width	35.49	3.78	35.68	3.75	-0.19	0.91	0.971	n/s
Mandibular intercanine width	26.51	2.95	26.55	2.78	-0.04	0.70	0.972	n/s
Maxillary intermolar width	44.24	2.88	43.63	2.33	0.62	1.87	0.761	n/s
Mandibular intermolar width	43.48	3.72	43.75	3.67	-0.27	0.61	0.986	n/s
Maxillary space available	73.83	4.64	73.85	4.68	-0.02	0.84	0.984	n/s
Mandibular space available	64.93	4.58	65.31	4.73	-0.38	2.39	0.968	n/s
Maxillary space required	69.76	9.32	69.57	9.14	0.19	1.04	0.994	n/s
Mandibular space required	63.76	6.34	63.51	5.97	0.24	0.95	0.990	n/s

***: significant at p≤0.05; **: significant at p≤0.01; ***: significant at p≤0.001; n/s: not significant**

APPENDIX 1
Raw Data
Measurements for Reliability

TABLE 2.--Abbreviations

OJDC	Overjet digital caliper
OBDC	Overbite digital caliper
MXCDC	Maxillary intercanine width digital caliper
MDCDC	Mandibular intercanine width digital caliper
MXMDC	Maxillary intermolar width digital caliper
MDMDC	Mandibular intermolar width digital caliper
MXSADC	Maxillary space available digital caliper
MDSADC	Mandibular space available digital caliper
MXSRDC	Maxillary space required digital caliper
MDSRDC	Mandibular space required digital caliper
Ojct	Overjet CBCT
Obct	Overbite CBCT
Mxcct	Maxillary intercanine width CBCT
Mdcct	Mandibular intercanine width CBCT
Mxmct	Maxillary intermolar width CBCT
Mdmct	Mandibular intermolar width CBCT
Mxsact	Maxillary space available CBCT
Mdsact	Mandibular space available CBCT
Mxsrct	Maxillary space required CBCT
mdsrct	Mandibular space required CBCT

TABLE 3.--Measurements from Digital Caliper (reliability)

	OJDC1	OJDC2	OBDC1	OBDC2	MXCDC1	MXCDC2	MDCDC1	MDCDC2	MXMDC1	MXMDC2	MDMDC1	MDMDC2	MXSADC1	MXSADC2	MDSADC1	MDSADC2	MXSRDC1	MXSRDC2	MDSRDC1	MDSRDC2
bb1163	2.5	2.5	1.9	1.8	34.7	34.7	26.9	26.6	47.9	47.8	44.1	43.9	67.8	67.7	59.5	59.7	66.2	66.3	59.9	59.4
bb1249	1.1	1.1	1.5	1.3	28.7	28.8	21.7	21.7	40.7	41.0	40.3	40.3	69.2	69.1	65.4	65.2	60.7	60.6	68.9	68.6
bb2563	1.8	1.9	0.8	0.7	36.1	35.9	31.0	31.0	46.9	46.4	43.8	44.0	75.0	74.4	75.8	75.9	82.0	82.2	70.4	70.4
bb1548	3.5	3.6	3.8	3.8	41.9	42.1	23.6	23.6	41.1	41.0	41.1	41.1	68.5	68.5	61.0	61.3	57.0	57.1	62.7	61.2
bb394	0.7	0.9	-1.0	-0.9	30.4	30.5	22.6	22.4	44.4	44.2	42.9	43.0	70.3	70.3	63.4	62.5	62.1	61.8	63.4	62.9
bb1515	1.9	1.6	-1.5	-1.7	43.3	43.6	32.0	31.8	42.3	41.8	37.8	37.6	63.2	63.9	55.7	55.6	55.6	55.3	55.9	55.8
bb656	2.6	2.2	1.2	1.3	37.7	38.1	28.3	29.2	44.1	44.2	42.9	43.2	77.8	77.5	66.4	65.9	80.1	79.7	65.0	64.2
bb3540	5.5	5.6	10.0	10.4	40.1	40.1	23.4	23.9	42.5	42.6	38.0	38.2	82.9	83.2	66.0	65.8	82.4	83.1	71.0	70.9
bb412	1.3	1.2	1.1	1.2	37.9	38.1	30.8	31.0	48.2	48.1	41.3	41.3	75.5	75.6	62.9	63.4	66.4	65.9	55.6	55.3
bb9681	3.2	3.1	2.9	2.7	33.2	33.6	26.6	26.9	39.3	39.3	43.5	43.4	72.1	70.9	65.2	65.1	72.4	72.0	66.1	65.5
bb100	1.3	1.3	1.2	1.3	31.1	30.7	21.6	21.3	39.2	39.2	39.7	39.7	71.7	71.6	64.9	64.8	71.9	72.3	64.7	64.7
a200	-1.8	-1.6	-2.2	-1.9	38.4	38.3	27.7	27.6	44.0	43.6	46.8	46.9	73.9	73.0	67.4	67.3	75.7	76.3	65.8	66.0

TABLE 4.--Measurements from CBCT (reliability)

	ojct1	ojct2	obct1	obct2	mxcct1	mxcct2	mdcct1	mdcct2	mxmct1	mxmct2	mdmct1	mdmct2	mxsact1	mxsact2	mdsact1	mdsact2	mxsrct1	mxsrct2	mdsrct1	mdsrct2
bb1163	2.7	2.7	1.9	1.8	34.9	35.5	25.4	25.6	44.9	44.6	43.9	44.1	67.9	67.8	59.0	59.2	65.0	64.8	59.5	58.8
bb1249	1.3	1.5	1.4	1.3	28.4	28.2	21.1	21.1	40.4	40.5	40.2	40.9	69.0	69.2	65.2	65.2	59.2	59.5	67.6	68.1
bb2563	2.9	2.8	1.0	0.8	34.7	34.9	30.6	30.7	44.2	44.8	44.0	43.5	74.8	74.9	75.8	76.3	81.6	81.7	70.3	70.9
bb1548	3.9	4.0	3.1	3.2	40.9	40.8	23.0	23.9	40.7	39.7	41.8	42.3	65.7	65.7	59.7	60.0	55.8	55.9	59.7	59.8
bb394	1.5	1.3	0.0	-0.6	30.6	30.8	22.6	22.3	43.8	43.6	43.3	43.3	70.0	69.3	59.3	59.5	59.6	59.6	62.4	62.7
bb1515	0.8	0.8	-1.4	-1.4	43.0	42.4	30.8	31.0	41.0	40.5	36.8	36.7	63.0	63.4	54.5	55.3	54.7	53.8	55.1	55.4
bb656	2.9	2.7	0.9	1.0	37.9	37.8	27.5	27.3	44.7	44.1	44.2	44.3	77.9	77.7	65.3	65.0	78.8	77.6	63.1	63.9
bb3540	4.2	4.8	10.4	10.4	40.4	39.9	23.1	23.6	42.3	41.2	38.0	39.0	80.9	82.0	65.1	64.3	81.4	81.5	69.7	69.1
bb412	0.9	1.0	-1.8	-1.8	36.7	37.7	29.9	29.4	41.1	41.7	41.5	41.7	74.3	73.9	63.5	63.6	65.2	66.3	55.3	54.6
bb9681	3.5	3.6	4.4	4.2	33.5	33.8	26.3	26.2	43.5	43.2	44.6	44.2	69.6	69.7	59.3	58.9	70.6	70.9	64.2	62.9
bb100	2.5	2.6	2.4	2.5	29.0	30.5	21.7	21.4	36.4	37.8	39.1	38.4	70.6	69.9	62.5	62.2	69.3	69.9	61.9	63.1
a200	-1.5	-1.6	-2.0	-2.0	38.8	38.8	27.9	27.6	43.6	42.9	47.5	47.4	72.4	72.8	66.7	66.1	76.5	76.6	65.3	65.2

TABLE 5.--Measurements from Digital Caliper (accuracy)

	OJDC	OBDC	MXCDC	MDCDC	MXMDC	MDMDC	MXSADC	MDSADC	MXSRDC	MDSRDC
bb1163	2.5	1.9	34.7	26.9	47.9	44.1	67.8	59.5	66.2	59.9
bb1249	1.1	1.5	28.7	21.7	40.7	40.3	69.2	65.4	60.7	68.9
bb2563	1.8	0.8	36.1	31.0	46.9	43.8	75.0	75.8	82.0	70.4
bb1548	3.5	3.8	41.9	23.6	41.1	41.1	68.5	61.0	57.0	62.7
bb394	0.7	-1.0	30.4	22.6	44.4	42.9	70.3	63.4	62.1	63.4
bb1515	1.9	-1.5	43.3	32.0	42.3	37.8	63.2	55.7	55.6	55.9
bb656	2.6	1.2	37.7	28.3	44.1	42.9	77.8	66.4	80.1	65.0
bb3540	5.5	10.0	40.1	23.4	42.5	38.0	82.9	66.0	82.4	71.0
bb412	1.3	1.1	37.9	30.8	48.2	41.3	75.5	62.9	66.4	55.6
bb9681	3.2	2.9	33.2	26.6	39.3	43.5	72.1	65.2	72.4	66.1
bb100	1.3	1.2	31.1	21.6	39.2	39.7	71.7	64.9	71.9	64.7
a200	-1.8	-2.2	38.4	27.7	44.0	46.8	73.9	67.4	75.7	65.8
a73	3.3	-6.7	32.8	27.2	43.5	37.9	73.1	65.6	69.1	53.5
a110	4.2	-8.2	32.9	23.8	39.3	38.6	70.7	60.4	53.3	50.4
a86-5	5.2	-5.0	35.2	22.8	38.7	40.5	73.9	57.3	72.5	56.0
a61	3.3	2.8	33.7	23.6	47.3	42.4	73.7	60.8	62.0	58.7
a104	-8.3	2.2	31.1	24.8	44.7	44.9	64.6	60.6	44.4	53.8
bb300	-0.9	0.5	35.0	23.6	44.4	44.8	72.5	58.6	62.5	59.4
hth858	1.5	-0.4	35.0	28.5	44.7	44.0	79.8	70.2	79.1	70.9
hth862	3.1	0.5	37.1	28.4	46.2	46.0	82.2	72.1	79.8	73.7
hth860	0.8	0.4	44.7	27.1	48.8	47.5	75.9	71.3	70.4	75.7
hth857	2.0	1.2	37.5	29.6	48.8	46.6	76.9	68.3	72.3	70.3
hth859	1.6	4.1	35.7	27.7	46.6	48.7	71.1	68.4	71.4	68.1
hth855	4.7	1.4	32.8	27.2	45.4	54.2	74.9	65.2	73.8	60.7
hth913	2.7	1.7	38.2	30.0	44.3	45.1	77.6	68.5	76.1	66.5
hth955	2.2	1.8	35.9	26.3	46.2	45.4	74.6	65.4	70.1	61.5
hth744	2.8	2.1	34.4	25.4	43.3	47.3	77.0	65.7	77.2	66.2
hth765	1.5	0.0	35.3	28.2	45.2	43.0	81.1	69.5	82.7	65.6
hth1009	-2.2	-3.2	30.5	24.4	45.7	46.3	73.9	65.2	70.8	66.7
hth620	1.9	-0.1	33.6	30.6	43.8	39.1	73.6	61.5	73.2	65.8

TABLE 6.--Measurements from CBCT (accuracy)

	ojct	obct	mxcct	mdcct	mxmct	mdmct	mxsact	mdsact	mxsrct	mdsrct
bb1163	2.7	1.9	34.9	25.4	44.9	43.9	67.9	59.0	65.0	59.5
bb1249	1.3	1.4	28.4	21.1	40.4	40.2	69.0	65.2	59.2	67.6
bb2563	2.9	1.0	34.7	30.6	44.2	44.0	74.8	75.8	81.6	70.3
bb1548	3.9	3.1	40.9	23.0	40.7	41.8	65.7	59.7	55.8	59.7
bb394	1.5	0.0	30.6	23.3	43.8	43.3	70.0	59.3	59.6	62.4
bb1515	0.8	-1.4	43.0	30.8	41.0	36.8	63.0	54.5	54.7	55.1
bb656	2.9	0.9	37.9	27.5	44.7	44.2	77.9	65.3	78.8	63.1
bb3540	4.2	10.4	40.4	23.1	42.3	38.0	80.9	65.1	81.4	69.7
bb412	0.9	-1.8	36.7	29.9	41.1	41.5	74.3	62.1	65.2	55.3
bb9681	3.5	4.4	33.5	26.3	43.5	44.6	69.6	59.3	70.6	64.2
bb100	2.5	2.4	29.0	21.7	36.4	39.1	70.6	62.5	69.3	61.9
a200	-1.5	-2.0	38.8	27.9	43.6	47.5	72.4	66.7	76.5	65.3
a73	3.6	-6.2	32.9	27.7	43.2	37.8	71.9	64.9	68.6	52.5
a110	4.2	-8.4	32.2	23.7	39.8	38.9	69.3	60.3	52.0	49.5
a86-5	4.9	-5.2	35.5	23.4	40.3	40.9	72.4	57.1	71.3	55.8
a61	3.5	2.8	33.0	22.1	45.3	42.6	73.8	60.0	61.7	58.0
a104	-9.1	2.5	30.7	24.5	44.5	45.0	62.4	60.2	44.3	52.1
bb300	-0.8	0.4	32.7	24.0	45.0	44.3	71.0	58.7	62.5	58.3
hth858	1.4	0.0	37.0	28.3	44.4	43.3	78.7	68.1	77.5	67.3
hth862	3.0	0.9	35.7	28.7	46.3	46.7	79.8	71.2	76.3	71.0
hth860	0.9	0.4	44.1	26.8	47.6	47.9	74.9	70.8	70.1	72.6
hth857	1.9	1.0	37.7	29.0	46.0	46.4	76.6	68.3	69.3	68.7
hth859	1.1	3.4	36.5	27.0	45.8	48.0	70.1	67.2	69.7	66.3
hth855	3.8	1.5	33.0	26.8	44.0	53.3	75.0	63.3	73.4	59.1
hth913	2.7	1.7	37.6	29.4	42.4	45.0	76.8	67.7	72.6	64.9
hth955	2.7	1.1	35.9	26.1	43.5	45.3	72.7	64.8	67.8	61.3
hth744	2.8	2.5	35.3	26.1	42.6	46.2	76.0	64.0	76.2	65.3
hth765	1.7	0.0	35.6	27.8	44.4	43.3	80.6	69.5	81.0	64.4
hth1009	-1.9	-3.1	31.7	23.8	45.1	45.8	72.2	65.1	70.0	65.7
hth620	1.1	-0.2	35.1	30.3	43.6	38.6	72.3	60.7	72.7	65.6

APPENDIX 2

Statistics

TABLE 7.--Paired Samples Statistics (reliability)

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	OJDC1	01.968	12	1.7707	0.5112
	OJDC2	01.946	12	1.7363	0.5012
Pair 2	OBDC1	01.631	12	3.1577	0.9115
	OBDC2	01.659	12	3.2234	0.9305
Pair 3	MXCDC1	36.124	12	4.6285	1.3361
	MXCDC2	36.189	12	4.6890	1.3536
Pair 4	MDCDC1	26.342	12	3.7410	1.0799
	MDCDC2	26.413	12	3.8110	1.1002
Pair 5	MXMDC1	43.383	12	3.0955	0.8936
	MXMDC2	43.259	12	3.0252	0.8733
Pair 6	MDMDC1	41.843	12	2.6456	0.7637
	MDMDC2	41.893	12	2.6894	0.7764
Pair 7	MXSADC1	72.331	12	5.1802	1.4954
	MXSADC2	72.141	12	5.0854	1.4680
Pair 8	MDSADC1	64.464	12	4.8729	1.4067
	MDSADC2	64.357	12	4.8577	1.4023
Pair 9	MXSRDC1	69.366	12	9.4885	2.7391
	MXSRDC2	69.388	12	9.6673	2.7907
Pair 10	MDSRDC1	64.105	12	5.0296	1.4519
	MDSRDC2	63.728	12	5.1213	1.4784
Pair 11	ojct1	02.133	12	1.6093	0.4646
	ojct2	02.183	12	1.7087	0.4933
Pair 12	obct1	01.692	12	3.3727	0.9736
	obct2	01.617	12	3.3986	0.9811
Pair 13	mxcct1	35.733	12	4.7532	1.3721
	mxcct2	35.925	12	4.4471	1.2838
Pair 14	mdcct1	26.408	12	3.6530	1.0545
	mdcct2	26.408	12	3.4592	0.9986
Pair 15	mxmct1	42.217	12	2.4409	0.7046
	mxmct2	42.050	12	2.1732	0.6273
Pair 16	mdmct1	42.333	12	3.3022	0.9533
	mdmct2	42.392	12	3.1799	0.9180
Pair 17	Mxsact1	71.533	12	4.9131	1.4183
	Mxsact2	71.383	12	5.1490	1.4864
Pair 18	Mdsact1	63.075	12	5.4973	1.5869
	Mdsact2	63.000	12	5.3988	1.5585
Pair 19	Mxsrct1	68.142	12	9.7803	2.8233
	Mxsrct2	68.175	12	9.7780	2.8227
Pair 20	Mdsrct1	63.025	12	5.3039	1.5311
	Mdsrct2	63.050	12	5.4368	1.5695

TABLE 8.--Paired Samples Correlations (reliability)

		N	Correlation	Sig.
Pair 1	OJDC1 & OJDC2	12	0.995	0.000
Pair 2	OBDC1 & OBDC2	12	0.999	0.000
Pair 3	MXCDC1 & MXCDC2	12	0.999	0.000
Pair 4	MDCDC1 & MDCDC2	12	0.995	0.000
Pair 5	MXMDC1 & MXMDC2	12	0.997	0.000
Pair 6	MDMDC1 & MDMDC2	12	0.998	0.000
Pair 7	MXSADC1 & MXSADC2	12	0.995	0.000
Pair 8	MDSADC1 & MDSADC2	12	0.997	0.000
Pair 9	MXSRDC1 & MXSRDC2	12	0.999	0.000
Pair 10	MDSRDC1 & MDSRDC2	12	0.996	0.000
Pair 11	ojct1 & ojct2	12	0.993	0.000
Pair 12	obct1 & obct2	12	0.998	0.000
Pair 13	mxcct1 & mxcct2	12	0.994	0.000
Pair 14	mdcct1 & mdcct2	12	0.994	0.000
Pair 15	mxmct1 & mxmct2	12	0.956	0.000
Pair 16	mdmct1 & mdmct2	12	0.989	0.000
Pair 17	mxsact1 & mxsact2	12	0.995	0.000
Pair 18	mdsact1 & mdsact2	12	0.996	0.000
Pair 19	mxsrct1 & mxsrct2	12	0.998	0.000
Pair 20	mdsrct1 & mdsrct2	12	0.991	0.000

TABLE 9.--Paired Samples Statistics (accuracy)

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	OJDC	01.764	30	2.5955	0.4739
	ojct	01.770	30	2.6300	0.4802
Pair 2	OBDC	00.487	30	3.3562	0.6128
	obct	00.513	30	3.4121	0.6230
Pair 3	MXCDC	35.493	30	3.7782	0.6898
	mxcct	35.367	30	3.7646	0.6873
Pair 4	MDCDC	26.513	30	2.9530	0.5391
	mdcct	26.203	30	2.8168	0.5143
Pair 5	MXMDC	44.243	30	2.8760	0.5251
	mxmct	43.347	30	2.3323	0.4258
Pair 6	MDMDC	43.479	30	3.7160	0.6784
	mdmct	43.473	30	3.6718	0.6704
Pair 7	MXSADC	73.834	30	4.6402	0.8472
	mxsact	72.753	30	4.6753	0.8536
Pair 8	MDSADC	64.933	30	4.5847	0.8370
	mdsact	63.880	30	4.7548	0.8681
Pair 9	MXSRDC	69.764	30	9.3162	1.7009
	mxsrct	68.490	30	9.1443	1.6695
Pair 10	MDSRDC	63.757	30	6.3395	1.1574
	mdsrct	62.417	30	5.9699	1.0900

TABLE 10.--Paired Samples Correlations (accuracy)

		N	Correlation	Sig.
Pair 1	OJDC & ojct	30	0.975	0.000
Pair 2	OBDC & obct	30	0.976	0.000
Pair 3	MXCDC & mxcct	30	0.967	0.000
Pair 4	MDCDC & mdcct	30	0.981	0.000
Pair 5	MXMDC & mxmct	30	0.761	0.000
Pair 6	MDMDC & mdmct	30	0.986	0.000
Pair 7	MXSADC & mxsact	30	0.984	0.000
Pair 8	MDSADC & mdsact	30	0.963	0.000
Pair 9	MXSRDC & mxsrct	30	0.994	0.000
Pair 10	MDSRDC & mdsrct	30	0.990	0.000

TABLE 11.--Paired Samples T-Test(accuracy)

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	OJDC - ojct	-,0063	,5859	,1070	-,2251	,2124	-,059	29	,953
Pair 2	OBDC - obct	-,0263	,7417	,1354	-,3033	,2506	-,194	29	,847
Pair 3	MXCDC - mxcct	,1263	,9713	,1773	-,2364	,4890	,712	29	,482
Pair 4	MDCDC - mdcct	,3093	,5749	,1050	,0946	,5240	2,947	29	,006
Pair 5	MXMDC - mxmct	,8960	1,8705	,3415	,1976	1,5944	2,624	29	,014
Pair 6	MDMDC - mdmct	,0060	,6094	,1113	-,2216	,2336	,054	29	,957
Pair 7	MXSADC - mxsact	1,0803	,8409	,1535	,7663	1,3943	7,037	29	,000
Pair 8	MDSADC - mdsact	1,0533	1,2736	,2325	,5778	1,5289	4,530	29	,000
Pair 9	MXSRDC - mxsrct	1,2737	1,0218	,1865	,8921	1,6552	6,828	29	,000
Pair 10	MDSRDC - mdsrct	1,3407	,9529	,1740	,9849	1,6965	7,706	29	,000

REFERENCES

Aboudara CA, Hatcher D, Nielsen IL, Miller A. A three-dimensional evaluation of the upper airway in adolescents. Orthod Craniofac Res. 2003;6 Suppl 1:173-5.

Abrahams JJ. Anatomy of the jaw revisited with a dental CT software program. Am J Neuroradiol. 1993;14:979-990.

Ackerman JL, Proffit WR. The characteristics of malocclusion: a modern approach to classification and diagnosis. Am J Orthod. 1969 Nov;56(5):443-54.

Alcaniz M, Montserrat C, Grau V, Chinesta F, Ramon A, Albalat S. An advanced system for the simulation and planning of orthodontic treatment. Med Image Anal. 1998; 2:61-77.

Aranyarachkul P, Caruso J, Gantes B, Schulz E, Riggs M, Dus I, Yamada JM, Criger M. Bone density asessments of dental implant sites: 2. Quantitative cone-beam computerized tomography. Int J Oral Maxillofac Implants. 2005;20(3)416-24.

Bell A, Ayoub AF, Siebert P. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. J Orthod. 2003;30 (3):219-23.

Benjamin LS. Versatility of the subperiosteal implant utilizing CAD-CAM multiplanar diagnostic imaging. J Oral Implantol. 1987;13(2):282-96.

Bidgewood WD Jr, Horii SC. Introduction to the ARC-Nema Dicom standard. Radiolographics; 1992 Mar;12(2):345-55.

Binder RE, Cohen SM. Clinical evaluation of tooth size discrepancy. J Clin Orthod. 1998; 32:544-546.

Cavalcanti MG, Ruprecht A, Vannier MW. 3-D volume rendering using multislice CT for dental implants. Dentomaxillofac Radiol. 2002 Jul;31(4):218-23.

Champagne M. Reliability of measurements from photocopies of study models. J Clin Orthod. 1992;26:648-650.

Commer P, Bourauel C, Maier K, Jager A. Construction and testing of a computer-based intraoral laser scanner for determining tooth positions. Med Eng Phys. 2000;22:625-635.

Danforth RA. Cone beam volume tomography: a new digital imaging option for dentistry.J Calif Dent Assoc. 2003 Nov;31(11):814-5.

Dus I. Why the Newtom is not a CT scanner. Document report, Aperio, Inc. Oct. 2002.

Feldkamp LA, Davis LC, Kress JW Practical cone-beam algorithm. J Opt Soc Am A (1984)1: 612.

Frederiksen NL. Diagnostic imaging in dental implantology. Oral Surg Oral Med Oral Path Oral Radiol Endod. 1995;80:540-554.

Garib DG, Henriques JF, Janson G, Freitas MR, Coelho RA. Rapid maxillary expansion--tooth tissue-borne versus tooth-borne expanders: a computed tomography evaluation of dentoskeletal effects. Angle Orthod. 2005 Jul;75(4):548-57.

Garino F, Garino, GB. Comparison of dental arch measurements between stone and digital dental casts. World J Orthod. 2002;3:250-254.

Han KU, Vig KWL, Weintraub JA, Vig PS, Kowalski CJ. Consistency of orthodontic treatment decisions relative to diagnostic records. Am J Orthod Dentofacial Orthop. 1991;100(3):212-219.

Hilgers ML, Scarfe WC, Scheetz JP, Farman AG. Accuracy of linear temporomandibular joint measurements with cone beam computed tomography and digital cephalometric radiography. Am J Orthod Dentofacial Orthop. 2005;

128:803-11.

Hunter WS, Priest WR. Errors and discrepancy in measurement of tooth sizes. J Dent Res. 1960;39:405-414.

International Commission on Radiological Protection. Publication 87. Managing Patient Dose in Computed Tomography. Oxford: Pergamon Press. Annals of the ICRP. 2001 Vol. 30/4.

Invisalign. www.invisalign.com, accessed October 2005. Align Technologies, Santa Clara, California.

Jaffray DA, Siewerdsen JH. Cone-beam computed tomography with a flat-panel imager: initial performance characterization. Med Phys 2000;27:1311-23.

Joffe L. OrthoCad: digital models for a digital era. Br J Orthod 2004 Dec; 31 (4):344-347.

Kau CH, Palomo JM, Hans MG. Three-Dimensional cone beam computerized tomography in orthodontics. J Orthod, in press.

Kitai N, Fujii Y, Murakami S, Takada K. Three-dimensional evaluation of a rare case with multiple impacted teeth using CT. J Clin Pediatr Dent. 2003;27(2):117-21.

Kuroda T, Motohashi N, Tominaga R, Iwata K. Three-dimensional dental cast analyzing system using laser scanning. Am J Orthod Dentofacial Orthop. 1996; 110:365-369.

Kyung SH, Park YC, Pae EK. Obstructive sleep apnea patients with the oral appliance experience pharyngeal size and shape changes in three dimensions. Angle Orthod. 2005;75(1)15-22.

Lascala CA, Panella J, Marques MM. Analysis of the accuracy of linear measurements obtained by cone beam computed tomography (CBCT-NewTom). Dentomaxillofac Radiol. 2004 Sep;33(5):291-4.

Lowley MN. The development of a new method of cephalometric and study cast mensuration with a computer

controlled video image capture system. Part II: study cast mensuration. Br J Orthod. 1993;20:203-14.

Lowley MN. The development of a new method of cephalometric and study cast mensuration with a computer controlled video image capture system. Part II: study cast mensuration. Br J Orthod. 1993; 20:315-331.

Ludlow JB, Davies-Ludlow LE, Brooks SL. Dosimetry of two extraoral direct digital imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. Dentomaxillofac Radiol. 2003 Jul;32(4):229-34.

Mah JK, Danforth RA, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. Oral Surg Oral Med Oral Path Oral Radiol endod. 2003;96:508-513.

Mah JK, Hatcher D. Current status and future needs in craniofacial imaging. Orthod Craniofacial Res, 2003;6 suppl. 1:10-16.

Marsh JL, Vannier MW. The 'third' dimension in craniofacial surgery. Plast Reconstr Surg 1983;71:759-67.

McDavid WD, Dove SB, Welander U, Tronje G. Direct digital extraoral radiography of the head and neck with a solid-state linear x-ray detector. Oral Surg, Oral Med, Oral Path. 1992 Dec;74(6):811-817.

Michael G. X-ray computed tomography. Physics Educ. 2001; 36:442-451.

Miles DA, Van Dis ML. Implant radiology. DCNA 1993;37;645-668.

Mok KH, Cooke MS. Space analysis: a comparison between sonic digitization (DigiGraph Workstation) and the digital caliper. Eur J Orthod. 1998;20:653-661.

Moore WS. Cone beam CT: a new tool for esthetic implant planning. Tex Dent J. 2005 Apr;122(4):334-40.

Motohashi N, Kuroda T. A 3D computer-aided design system applied to diagnosis and treatment planning in

orthodontics and orthognathic surgery. Eur J Orthod. 1999;21:263-274.

Mozzo P, Poracci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. EurRadiol 1998;8(9):1558-64.

Naccache H, Bernard C, Brodeur JM, Pournier A. Epidemiological evaluation of a computerized diagnosis in orthodontics. J Dent Res. 1989;68:776.

Ning R, Tang X, Conover D, Yu R. Flat panel detector-based cone beam computed tomography with a circle-plus-two-arcs data acquisition orbit: preliminary phantom study. Medical Physics 2003;30(7):1694-1705.

Ogawa T, Enciso R, Memon A, Mah JK, Clark GT. Evaluation of 3D airway imaging of obstructive sleep apnea with cone-beam computed tomography. Stud Health Technol Inform.2005;111:365-368.

Palomo JM, Hans MG. Three-Dimensional Craniofacial Imaging in Orthodontics. J Med Sci; in press.

Proffit WR. Orthodontic diagnosis: the development of a problem list. In Proffit WR, Fields HW, eds. Contemporary Orthodontics. 3rd edition St. Louis: Mosby; 2000:165-170.

Quimby ML, Vig KWL, Rashid RG, Firestone AR. The accuracy and reliability of measurements made on computer-Based digital models. Angle Orthod. 2004;74:298-303.

Redmond WR, Redmond WJ, Redmond MJ. Clinical implications of digital orthodontics Am J Orthod Dentofacial Orthop 2000;117:240-1.

Redmond WJ, Redmond MJ, Redmond WR. The OrthoCAD bracket placement solution. Am J Orthod Dentofacial Orthop. 2004;125(5):645-6.

Romeo A, Canal F, Roma M, de la Higuera B, Ustrell JM, von Arx JD. Holograms in orthodontics: a universal system for the production, development, and illumination of holograms for the storage and analysis of dental casts.

Am J Orthod Dentofacial Orthop. 1995;108(4):443-447.

Rossouw PE, Benatar M, Stander I, Wynchank S. A critical comparison of three methods for measuring dental models. J Dent Assoc S Afr. 1991;46(4):223-6.

Ryden H, Bjelkhagen, H, Martensson, B. Tooth position measurements on dental casts using holographic images. Am J Orthod. 1982;81:310-313.

Santler G, Karcher H, Ruda C. Indications and limitations of three-dimensional models in cranio-maxillofacial surgery. J Craniomaxillofac Surg. 1998 Feb;26(1):11-6.

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

Schirmer UR, Wiltshire WA. Manual and computer aided space analysis: a comparative study. Am J Orthod Dentofacial Orthop. 1997;112:676-680.

Scholz RP. Considerations in selecting a digital camera for orthodontic records. Am J Orthod Dentofacial Orthop. 1998 Nov;114(5):603-5.

Schwarz MS, Rothman SLG, Rhodes ML, Chafetz N. Computed tomography: Part I. Preoperative assessment of the mandible for endosseous implant surgery. Int J Oral Maxillofac Implants. 1987;2:137-48.

Seo K, Ueno K, Matsuoka M, Kanou M, Yamamoto K, Tanaka K, Okabe K, Hibino A. Development of dento-maxillofacial cone beam X-ray computed tomography system. Extracted from MEDIX VOL.37 P.40~45, Hitachi Medical Corporation.

Shellhart WC, Lange DW, Kluemper GT, Hicks EP, Kaplan AL. Reliability of the Bolton tooth size analysis when applied to crowded dentitions. Angle Orthod. 1995; 65:327-334.

Sheridan JJ. The readers corner. J Clin Orthod. 2000; 34: 593-597.

Sohmura T, Kojima T, Wakabayashi K, Takahashi J. Use of an ultrahigh-speed laser scanner for constructing three-dimensional shapes of dentition and occlusion. J Prosthet Dent. 2000; 84:345-352.

Sohmura T, Wakabayashi K, Lowmunkong R, Hojo H, Kusumoto N, Okuda H, Kojima T, Nakamura T, Yatani H, Takahashi J. 3-D shape measurement of dental casts using medical X-ray CT. Dent Mater J. 2004 Jun;23(2):121-8.

Tomassetti JJ, Taloumis LJ, Denny JM, Fischer JR Jr. A comparison of 3 computerized bolton tooth-size analyses with a commonly used method. Angle Orthod. 2001;71:351-357.

Vannier MW. Craniofacial computed tomography scanning: technology, applications and future trends. Orthod Craniofacial Res. 6 (Suppl. 1) 2003;23-30.

Wakabayashi K, Sohmura T, Takahashi J, Kojima T, Akao T, Nakamura T, Takashima F, Maruyama T. Development of the computerized dental cast form analyzing system-three dimensional diagnosis of dental arch form and the investigation of measuring condition. Dent Mater J. 1997;16:180-190.

Weinberg LA. CT scan as a radiologic data base for optimum implant orientation. J Prosthet Dent. 1993 Apr;69(4):381-5.

Weed LL. Medical Records, Redical Education and Patient Care: the Problem-oriented Record as a Basic Tool. Cleveland: Case Western Reserve Press 1969.

White SC 1992 assessment of radiation risk from dental radiography. Dentomaxillofac Radiol 1992; 21:118-126.

Winter AA, Pollack AS, Frommer HH, Koenig L. Cone beam volumetric tomography vs. medical CT scanners. N Y State Dent J. 2005 Jun-Jul;71(4):28-33.

Wong BH. Invisalign A to Z. Am J Orthod Dentofacial Orthop. 2002; 121(5):540-1.

Yamamoto K, Ueno K, Seo K, Shinohara D. Development of dento-maxillofacial cone beam X-ray computed tomography system. Orthod Craniofac Res. 2003;6 Suppl 1:160-2.

Yamamoto K, Hayashi S, Nishikawa H, Nakamura S, Mikami T. Measurements of dental cast profile and three dimensional tooth movement during orthodontic treamtent. Trans Biomed Eng.1991;38:360-365.

Yamamoto K, Toshimitsu A, Mikami T, Hayashi S, Harada R, Nakamura S. Optical measurement of dental cast profile and application to analysis of three-dimensional tooth movement in orthodontics. Front Med Biol Eng. 1989;1(2):119-30.

Zilberman O, Huggare JAV, Parikakis KA. Evaluation of the validity of tooth size and arch width measurements using conventional and three-dimensional virtual orthodontic models. Angle Orthod. 2003;73:301-306.

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