Submitted by Nghia Ngoc Ho in partial fulfillment of the requirements for the degree of Master of Science in Oral Biology.

Accepted on behalf of the Faculty of the Graduate School by the thesis committee:

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COMPARING DIMENSIONAL ACCURACY BETWEEN A POLYVINYL CHLORIDE SKULL AND ITS VIRTUALLY CONSTRUCTED COUNTERPART

BY

NGHIA NGOC HO

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in the
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LIST OF ABBREVIATIONS

3D………………...Three Dimensional

PVC………………Polyvinyl Chloride

CBCT…………….Cone Beam Computed Tomograph

CAD/CAM……… Computer-Aided Design and Computer-Aided Manufacturing

ALARA…………..As Low As Reasonably Achievable

DICOM…………..Digital Imaging and Communication in Medicine

CT………..………Computed Tomography

MB……………..…Megabyte

kV………..………Kilo Voltage

mA……………..…milli Amperage

S…………………Second

mGy·cm^2………...milli Gray per square centimeter

mL……………….Milliliter

g…………………Gram

mm……………....Millimeter

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ABSTRACT

Objective: To determine if a life size skull replica representing the normal dimensions of a human skull and patient, can be accurately constructed into a three dimensional (3-D) image using digital dental casts, cone beam computed tomography (CBCT) and modern imaging software. Dimensional accuracy between the physical and virtual models are measured and verified using physical and computer markings. Measurements are compared to determine if the markings, i.e. physical and computer generated are identical.

Materials and Methods: A PVC skull replica was determined to be the ideal object to image and measure in this study since it represents a typical medical/dental patient requiring radiographic study using CBCT and other imaging software. It was necessary to make initial measurements and markings on the physical skull replica so that the virtual CBCT/digital image could be created and measured for dimensional accuracy to its physical counterpart. Irregular v-shaped notches approximately 2-3mm in height were made on the occlusal/incisal surface of each maxillary tooth from #2 to #15 using a rotary bur for points of measure. Linear measurements from each tooth to the cephalometric nasion (Na) on the skull (figure 12) were calculated using a digital caliper. To create the virtual model, a CBCT of the replica was taken with the Kodak 9500 Cone Beam 3D System. To create the digital dental models fifteen type IV maxillary dental casts were made on the replica and scanned into a digital format using Ortho Insight 3D system. The CBCT image was merged with the digital dental casts by aligning the tooth notches on the digitized casts to the notches on the CBCT. Dolphin Imaging software, Motion View Software, LLC, Carlsbad, CA, U.S.A., was used to create and measure the final virtual model. Measurements from each notch to nasion were taken and recorded.

Results: Statistical Analysis utilizing Student t-Test revealed no statistically significant difference between the linear measurements made on the PVC model to the linear measurements made on the 3-D virtual model.

Conclusion: Virtual digital models constructed from CBCT images and digital dental casts are dimensionally identical to physical counterparts composed of a PVC skull model and stone dental models.

This finding supports the null hypothesis and our statistical data that there is no dimensional difference between a CBCT/computer constructed image and its separate physical models.

INTRODUCTION

The tremendous advancement of digital technology in computer science over the last two decades has been rapidly changing to incorporate new digital developments into daily clinical operations. Film base dental radiographs and paper records once considered to be the gold standard are rapidly being replaced by modern digital technology [16]. Dental digital technologies such as patient digital records, digital radiographs, CAD/CAM technologies, CBCT, digital dental impressions, digital/virtual dental models have immensely changed the landscape of daily operations in the field of dentistry [4, 5, 16]. With newer and better technology dentists and other health care providers can be certain that the digital dental era is the future of modern dentistry and medicine [3, 9, 11, 13].

It is the hope of many dental professionals and engineers that the current digital technology will greatly improve in dimensional accuracy and quality so that conventional two dimensional 2-D radiographic operations in the dental office will be replaced by better 3-dimensional (3-D) digital technologies [19]. For many dental specialties especially the fields of periodontics, orthodontics and oral and maxillofacial surgery, there is a hope that this technology will eliminate the inadequate diagnostic quality of 2-D imaging and improve the ability of the practitioner to diagnose, treatment plan, and accurately perform measurements on a physical patient by manipulating the CBCT/digital virtual records [6]. Digital integration and reconstruction of these modalities to create a virtual patient are currently at a broad stage of development and there has been growing research into the quality and accuracy of this technology [4, 6, 9]. This study was designed to measure the dimensional accuracy of a PVC skull model and replicated stone dental casts to a digitally constructed virtual counterpart using current CBCT scan, digitized dental casts and other imaging software.

Cone Beam Computed Tomography (CBCT)

Since the discovery of X-ray images in 1895 by Wilhelm Conrad Roentgen, two dimensional x-ray images have greatly progressed the diagnostic capabilities of medicine and dentistry [2, 11]. Unfortunately two dimensional images lack a lot of information found in a multidimensional patient. The invention of computed tomography (CT) in the late 1970s by Hounsfield and Cormack was considered to be the most important and valuable medical invention since the discovery of X-rays [1]. Although this new technology offered numerous advantages over the conventional radiographic technique the high cost, high radiation exposure, and high operational skill limited its use in the average dental office. In the 1980s during the early days of CT, the cone beam computed tomography (CBCT) was introduced into the dental field but its use was limited to pathological evaluations of the head and neck as well to certain oral & maxillofacial surgeries. It was not until 1988 that cone beam computed tomography was re-engineered as commercially available to other dental practitioners [2-5].

With the conventional and digital radiographic modalities, images are produced by x-rays from an x-ray source and transmitted through soft and hard tissue to a film or digital sensor which processes or produces the image into a two dimensional duplicate [2, 4, 11]. Medical CT and CBCT technologies also use radiation and digital sensors in addition to complex algorithm software to capture images and reconstruct them into three dimensional images [11]. Medical CT captures images by using an X-ray source rotating around the patient emitting short bursts of thin fan shape radiation which projects these images onto a detector plate located opposite the source. A CBCT also uses cone shape radiation bursts from the source while it rotates 360 degrees around the patient and develops it into a three dimensional, 3-D image. In both mechanisms, both the source and the detector act as a unit as they move together to capture a complete image of the patient's anatomy [1-5, 10]. A major difference between medical CT and CBCT is how the images are acquired and reconstructed to form the 3-D images. Medical CT typically captures approximately about 200-500 axial slides with one scan of the object. Images are then "stacked" onto each other by the manufacturer's software to form a 3D image. CBCT acquires images by sweeping motions similar to panoramic radiography and the images are captured as a single 3-D volumetric image [2, 11]. After the data is processed, the software can be manipulated to perform a 3D reconstruction of the hard structures as well as a secondary reconstruction to produce a panoramic view from different angles [1-4, 6, 8, 11]. With newer CBCT machines and software, a CBCT can produce high resolution, more accurate 3-D images, and eliminate overlaps and distortion often associated with traditional 2-dimensional images [4, 7, 15].

The 3-D volumetric data of CBCT images are actually made up of many smaller cuboidal subunits known as voxels. Voxels are isotopic meaning they are equal in dimension. The size of these voxels dictates the resolution of the images. Voxels are isotropic which ranges from 0.4 millimeter to 0.125 millimeter in their size. The smaller the voxel, the more resolution power and therefore there is better image detail [3, 7, 8, 15]. B. Al-Rawi states that newer CBCT technology can offer higher spatial resolution with voxel size small as 80 micrometer [17]. Although having a high resolution image is generally desirable, clinicians need to have thorough working knowledge of CBCT regarding the advantages and disadvantages of acquiring high resolution CBCT images [2, 3, 7, 12, 14]. As the X-ray source and the reciprocal X-ray receptor rotate around the patient's head, multiple single cephalometric like images are captured onto the detector. The raw data collectively is also known as the projection data. The number of images captured depends on the frame rate (f/s), the trajectory arc width, and the rotational speed. All these parameters can be adjusted to accommodate the clinicians' preferences (eg, i-CAT, Imaging Sciences International, Hatfield, Pa; PreXion 3D, TeraRecon Inc, San mateo, Calif) or they are predetermined by the CBCT manufacturers (eg, Newtom 3G, QR Inc, Verona, Italy; Iluma, Imtec Inc, Ardmore, Okla;Galileos,Sirona AG, Bensheim, Germany, orPromax 3D, PanmecaOy, Helsinki, Finland) [8]. To acquire images with higher resolution, more single images are captured which increases scanning time, and the data set is much larger therefore this requires more processing time and computer storage space. The most important aspect of acquiring higher resolution images is that patients are being subjected to a higher dose of radiation [7, 8, 12, 14]. Therefore, when subjecting patients to ionizing radiation, clinicians need to apply the ALARA (as low as reasonably achievable) rule in order to make sound clinical decisions and still achieve the desired result [7]. Federal regulations require that CBCT data be stored as Digital Imaging and Communication in Medicine (DICOM) data format which is the standard for handling, storing, printing, and transmitting information in medical imaging. DICOM formating provides a uniform way of handling these images so that medical and dental providers have the same access at any time without the trouble of converting these images to a unsuitable format for viewing, i.e. tiff or jpeg. With compatible software, providers can view, diagnose, treatment plan and transfer image data that is consistent with each provider [4, 9].

When CBCT was first introduced to the dental community, it was only suitable for a small group of dental providers, especially oral and maxillofacial surgeons. This was due to its high cost and low resolution. Over the last decade, the CBCT technology has become significantly better in resolution plus the cost of CBCT technology has become more and more affordable to the dental community. With the many benefits that CBCT offers over traditional 2-D X-ray methods, we should expect it to be a more common fixture in the dental practice of the future [2-6].

For oral pathologists, CBCT images are undoubtedly an invaluable tool in visualizing pathological lesions and their severity. This not only eliminates the potential for multiple radiographs at different angles but this also provides the provider an exact location and size of a pathological lesion in a three dimensional orientation. This invaluable information can help pathologists and surgeons detail the treatment modality as well as inform the patient of the possible morbidity, outcome and sequela of their surgical procedure [3]. Perhaps the dental specialty that benefits the most from CBCT are the oral and maxillofacial surgeons. CBCT gives the surgeon high resolution 3-D images where they can diagnose and treatment plan various surgeries such as orthognathic, temporomandibular join (TMJ), and implant placements. Moreover, with 3-D planning software, surgeons are able to visualize the whole maxillomandibular complex in three dimensions. They can plan and perform virtual model surgery prior to the actual procedure [9].The advancements in digital communications and laboratory support have also brought many changes to the conventional methods used to manage facial reconstruction surgeries. Current 3-D CBCT technology allow surgeons to send the CBCT images to dental laboratories for producing stereolithographic models of the patient. Dental laboratories can also use the 3-D images to fabricate surgical guides, prosthetic joints, titanium plates and screws. From a surgical perspective, CBCT technology can not only help in diagnosis and treatment planning, but it also saves time by eliminating unnecessary lab work which can save time in the operating room [2, 3, 4, 9].

For the orthodontist a CBCT can provide a 3-D image of all hard structures of the jaw, provide a closer view of the sinus, bone levels, impacted teeth, and root proximities. In endodontics a CBCT can be a great tool in helping clinicians to visualize the root form, canal system, and extent of periapical lesions in relation to the paranasal sinuses, floor of the nasal cavity, cortical bone plate perforations, the inferior alveolar canal and mental foramen. In patients with complex root canal systems, a CBCT can help identify the canals, the anatomy of each and guide the clinician performing the endodontic treatment [13].

Before CBCT was widely available, dentists who performed dental implant placement performed bone sounding to determine alveolar bone thickness. Even though many clinicians are still using this technique for implant placement, CBCT offers clinicians an accurate indirect visualization of the alveolar ridge, root proximities, alveolar form and thickness. With the advantages the CBCT offers over the traditional method, clinicians can treatment plan and place implants with more confidence with fewer complications from problems such as implant orientation, cortical bone plate perforation, maxillary sinus perforation, and impingement on the inferior alveolar and mental nerve. Periodontists can also accurately visualize the extent of periodontal disease [2, 3, 4, 9, 11, 16].

Comparing the radiation dose of CBCT to medical CT, it was determined that the effective radiation dose of one CBCT ranges from 30 to 400 micro Svas compared to the effective radiation dose of one conventional medical CT of about 21,000 micro Sv. This is a drastic reduction in radiation exposure when compared to a typical medical CT scan. There are variations in the effective dose of a CBCT depending on the manufacturer but the effective dose is considerably lower than a medical CT scan. According to Mah, the average effective dose of radiation for a conventional and digital panoramic film is 3-11 micro Sv, lateral cephalometric is 5-7 micro Sv, PA cephalograph is 5-7 micro Sv, occlusal film is 5 micro Sv, full mouth series is 30-80 micro Sv, and TMJ series is 20-30 micro Sv [2]. Patients should not be subjected to an unnecessary exposure of radiation and clinicians who prescribe CBCT must determine the need on a case by case basis. Clinicians must determine the risk versus benefit and cost before obtaining a CBCT.

With careful planning and consideration, a CBCT can provide clinicians many advantages over two dimensional images. The average time of obtaining a CBCT is between 7 and 70 seconds [3]. The difference in time can vary from one manufacturer to another. As discussed above, rendering a high resolution CBCT requires more time capturing the data because of the increasing number of projections. Depending on the choice of image quality, images rendered with a lower resolution resulting in a lower radiation dose and less processing time can be just as diagnostically effective as images processed at a higher resolution. According to Brown and colleagues they found no reduction in dimensional accuracy by using a smaller dose of radiation [8]. From the time the CBCT was made available to the dental community, research was ongoing to determine the accuracy of calibrated CBCT images compared to scanned dental casts and other scanned physical structures, i.e. a human skull. Brown and colleagues found that the linear measurement difference between calibrated CBCT images and those measurements made directly on studied skulls were less than one millimeter and the relative percentage difference was less than 5%. Moreover they concluded that 3-D reconstructed images rendered at 153 projections have similar dimensional accuracy as compared to those rendered at 612 projections. 3-D reconstructed images can reduce the radiation dose up to 75% because of the smaller number of projections needed to process the image but only if resolution quality is not a major concern [8]. Al-Ekrish found that lowering the exposure time from 40 seconds to 20 seconds does not affect the reliability nor dimensional accuracy of implant sites [12].

Over the years, multiple studies have shown that CBCT images can have a clinical acceptable dimensional accuracy. Although CBCT machines offer greater resolution and image quality, CBCT machines were developed primarily for viewing large overall structures and not for intimate details such as the surface of a tooth. Moreover, a CBCT is not suitable for viewing soft tissue even at an optimal resolution. CBCT images rendered at a higher resolution produce smoother and more uniform hard tissue surfaces but this exposes the patient to a higher dose of radiation. Another drawback is the artifactual images produced by scattered X-rays from a metallic object. Metallic dental prostheses not only block out the passage of X-rays but also deflect the X-rays producing streaks of white artifacts or dark bands on the image that can obstruct the surrounding structures [4]. In an attempt to overcome this phenomenon, manufacturers have increased the resolution by increasing the number of projections captured producing a smoother 3-D reconstructed image. This method unfortunately increases the radiation dose to the patient. Artifacts also come from patient's movements during image rendering; this is known as a motion artifact. During the scanning process, patients must remain still until completion of the CBCT image. Object movement during this time causes blurring of all structures in the field of view [4]. Older CBCT technology had lower resolution with an inadequate filter resulting in radiation scatter and poor image quality. This is a common phenomenon often called "noise". As the X-ray source is moving around the object, the receptor is detecting and capturing non-uniform beams of radiation passing through the object. Objects of different densities can cause different degrees of X-ray scatter. Newer CBCT machines have better radiation filtering systems, more sensitive receptors, higher resolution and more complex algorithms that help overcome these disadvantages [4, 5, 7].

Although CBCT machines and software are widely available to the dental providers from many different manufacturers, the cost of a CBCT machine ranges from 150,000 to 300,000 dollars [4]. Due to its high cost, a CBCT machine for a small dental practice seems to offer no additional economic benefit. Many dental procedures can be performed safely and clinically acceptable without the aid of a CBCT, therefore purchasing the CBCT machine is not a practical move for the average dental provider. Purchasing a CBCT machine may be more useful and economical for a larger multidisciplinary dental practice. A group practice can also serve as the "imaging center" for smaller dental practices. Therefore, a private practitioner can order the CBCT at a distant site while still enjoying the benefits that the CBCT can offer at a much lower cost [4, 7].

Although a CBCT machine has been commercially available for the dental profession for many years there is still no formal training required for dentists using this technology. Unlike medicine where radiographic images are read and interpreted by a radiologist, the dental radiographic images are often ordered and read by the same dentist [11]. Although patients who are subjected to CBCT images are exposed to a much lower dose of radiation than a medical CT, dental providers need to be aware that the effective radiation dose of a CBCT is still much higher than other 2-D dental digital radiographs [3]. With a higher dose of radiation, patients are at higher risk of exposure. Consensus by the American Academy of Oral and Maxillofacial Radiology and the European Academy of DentoMaxilloFacial Radiology recommended that CBCT only be taken and interpreted by a licensed practitioner who is adequately trained in CBCT. They also recommend that CBCT images of the dento-aveloar region be interpreted by CBCT trained providers. Images that go beyond the floor of the nose or below the border of the mandible including other cervio-craniofacial structures should be performed and interpreted by maxillofacial radiologists. The Academy recommends ordering a CBCT only after a complete review of a patient's medical history and only if the benefit of taking a CBCT outweighs the radiation risk for the patient [11].

Digital Dental Models/Casts

Since the early 1700s, dental models made of gypsum base materials have been the primary method of obtaining records for dentists. The relative ease of use and the availability of gypsum product will continue the fabrication of dental models in most dental practices but the advent of digital dental technology will challenge it's place in the modern dental office [19, 22, 27, 34, 37]. Dental models can be produced quickly and are relatively inexpensive, however long term storage of these models poses a challenge for many practices. With the current advancements in dental digital technology, it is now possible for dentists to produce and store digital dental models indefinitely [22, 23, 24]. This will help the dentist save office space, reduce chairside procedures and eliminate the time fabricating study models.

The level of training required to obtain dental impressions and fabricate dental casts isn't difficult. These procedures are typically performed by dental assistants under the tutelage of the dentist. Taking the impression requires the patient to be sitting in the dental chair while the operator selects the size and type of impression tray. The tray must fit the dental arches but allow room for the impression material to take an accurate model of the hard and soft tissues. The assistant alternately places the trays in the mouth for a best "fit" not unlike trying on a new pair of shoes.

The tray can be a metal or plastic stock tray and both types can be disinfected and reused on multiple patients. An adhesive coating is applied to the trays for the impression material. Impressions can be taken with a multitude of materials based on working time, cost, dimensional accuracy, and pouring time. After the impressions are taken, the operator then fabricates the dental casts by mixing dental stone with water according to manufacturer's directions and pours the mixture into the patient's impressions. Once the dental casts are set the models can be separated from the impression and trimmed according to the dentist's desired dimensions and stored for future use.

Physical dental casts are made of gypsum base materials such as Plaster of Paris, type III and type IV dental stone. These materials have proven for many years to be an accurate replication of the dental arches [19, 34]. They are also dimensionally stable in storage [38]. Dentists also can fabricate oral appliances off of these dental records which is a testament to their accuracy. Physical casts can be also be duplicated with minimal cost to the provider [20, 27, 33]. Along with all the benefits of having the physical dental casts there are also many disadvantages. Producing the physical casts can take lab time as well as incur additional supply costs [18, 19, 20, 22]. Casts are prone to fracture if not handled with care and the materials used to fabricate the stone models if not handled properly on the patient and in the lab can contribute to errors in the final accuracy of the casts [24, 27, 34].

With all the above mentioned disadvantages of the physical casts, the most important disadvantage is the portability, transportation, storage, and longevity of the casts [19, 38]. Dental casts are heavy and bulky which make them difficult for transport to and from distant sites. Depending on the state regulations of patient dental records, dental casts must be kept for a minimum of 5 years and up to 15 years in most states. This is a big challenge for many dentists, especially orthodontists since most orthodontic patients require initial diagnostic casts as well as post treatment models. Long term storage of these casts poses a huge challenge for physical space and cost. As stated by Peluso et al., “A busy orthodontic office may start upward of 300 cases in 1 year, requiring an entire room for model storage…….Three hundred cases per year for 10 years equals 6000 sets of pretreatment and post-treatment models. This might necessitate an off-site facility with increasing cost to the practice” [19, 38].

To solve these inherent issues with gypsum base dental casts, today’s digital technologies have evolved to allow dentists to not only digitally produce and store dental casts but also to transition to an entirely digital patient based care [15]. In 1999, OrthoCAD™ was the first company to introduce a digital model service particularly targeting the orthodontic specialty [19, 23, 24]. In 2001, emodels™ by GeoDigm was introduced to the orthodontic community at the American Association of Orthodontists (AAO) National Meeting [35].

OrthoCAD™ is operated by Cadent Inc, in Fairview NJ. By applying CAD/CAM technology in dentistry, engineers in consult with clinicians and other computer software/hardware experts, were able to expand and build a 3-D virtual based dental model system. Clinicians who wish to utilize the digital model service provided by OrthoCAD™ can access a website to download the software or request the software to be sent free of charge. The cost of a set of digital models produced by OrthoCAD™ is about the same as the laboratory charge for a set of trimmed study casts [15]. Upon a request by the doctor, OrthoCAD™ will send a postage-paid next day shipping kit to the dental office. The company recommends the use of alginate impressions with disposable trays. Once the impressions are taken, the clinician will send them along with the wax bite registration overnight to its company or its affiliated laboratory for processing. When they receive the impressions and bite registration, OrthoCAD^{TM} will pour the impressions and use their proprietary process to scan the dental casts and convert them into a digital format. The digital casts are then articulated by their software based on the bite registration. The process takes about 5 days after which the clinician can access an OrthoCAD^{TM} website and view the digital dental casts. OrthoCAD^{TM} will save these files on their server for 10 years or clinicians can request longer storage on their server for a small fee. Clinicians can also download the digital files onto a personal computer or other distant servers [19, 31, 35].

OrthoCAD^{TM} also sends trimmed models to the dental offices or dental laboratories for appliance fabrication at the request of the clinician for an additional fee. OrthoCAD^{TM} will also digitalize any trimmed casts from previous cases [19].

Using OrthoCAD^{TM}software or other similar software such as Cecile3, also allows clinicians to view the 3-D articulated or non-articulated models simultaneously at different angles. The software allows clinicians to rotate and enlarge the models for visual enhancement of any particular area of the casts. Clinicians can perform measurements and analyses from any angle. Cross-sectioning tools allows clinicians to slide the models in any desired direction for further evaluation of symmetry, overjet, and overbite. The Jaw Alignment Tool enables clinicians to move the mandible in different directions to assess lateral excursive movements and occlusal contacts. A software function called Occlusogram is a multicolor representation of occlusal contacts, contact areas, and interarch spacing as well as occlusal spacing of opposing arches. For an additional charge, the clinician can access a OrthoCAD^{TM} Virtual Set-Up tool. This feature helps clinicians perform virtual treatment options including extractions, interproximal reductions, expansion, leveling, and the ability to fabricate and order hardware appliances such as indirect bracket placement systems and retainers [19, 26, 35] .

Currently, digital dental casts processed by OrthoCAD^{TM} can be viewed with compatible viewing software such as Dolphin Imaging, Vistadent, Walrus, Sirona, PraciceWorks Imaging, Dr. View, Oasys, Ortho II, IMS, Orthochart, Televox, and OrthoSesame [19].

Emodels^{TM} digital dental model service operates similar to the service provided by OrthoCAD^{TM} regarding free software, prepaid postage, overnight shipping kits, impression requirements and plaster cast fabrication for digitizing. With emodels^{TM}, clinicians can use disposable or metal trays. Using a nondestructive laser scanning process, the plaster casts digitally map with a +/- 0.1 mm accuracy of all surfaces. Like OrthoCAD^{TM}, the digital models are ready for view in 5 days and the company also maintains a digital copy on their server [15]. A set of emodels^{TM}digital casts is about 800 Kilobytes. For an additional charge, the company can send the plaster casts to a dental office or to a laboratory for hardware fabrication. After 4 weeks, the plaster casts are discarded. The software features of emodels^{TM} is similar to that of OrthoCAD^{TM} such as 3-D views, model sectioning, articulation, and *e*plan™. GeiDigmemodel™ files used by emodels™ are compatible for viewing with Dolphin, IMS, and Vistadent (GAC) [19].

Although this technology has been available to the dental profession since it was first introduced in 1999, the use of this technology is still very limited and the use of digital dental models in the daily operation of dental offices appears to be a small number of dental providers, especially orthodontists. This can be easily understood because all orthodontic patients require pretreatment and post-treatment study models. In addition, orthodontic treatment generally requires several years to complete, therefore long term storage of study models and records not only serves the purpose of diagnosis and treatment planning but also provides long term assessment for growth and development [23, 33]. Other dental specialties tend to use stone dental casts for making appliances, stents, waxups and surgical guides to facilitate their treatment plans but not for diagnosis, planning and storage. Typically the stone casts are discarded after treatment completion.

Digital models can be measured, digitally sectioned, viewed in 3-D, drawn upon, treatment planned for direct prosthodontic dental work and even bonded using virtual orthodontic brackets. Currently there are intraoral digital scanning devices that can allow the practitioner to scan the mouth directly to create digital models but the high costs of buying the scanner versus using cheaper dental materials is a major reason dentists are not using the new scanning technology. Dental impressions are a daily practice in any average dental office so dental casts are a common method of taking dental records over the more expensive and newer scanning devices. If digital dental records are used in the dental office today the impressions are taken, boxed and shipped to companies that can process, store and digitize theses records for the practitioner. The disadvantage when utilizing this method is that this requires accurate impressions made of stable materials that can withstand the negative physical and environmental factors of shipping and handling.

One of the impression materials with desired stable properties is polyvinylsiloxane or PVS. Unfortunately it's a lot more expensive than the alginate material normally used for making study casts. If impressions are taken with an alginate material they are required to be shipped overnight to the laboratory for processing and digitizing. The 4-5 days turnaround time is another major disadvantage of using digital study models. With conventional-in office methods, the physical casts can be ready for use in several hours or less depending on the setting time of the stone materials [19, 22]. Using intra-oral scanning technology dentists can produce digital dental models in their office without taking impressions or waiting for the 5 day processing time [19, 40]. CAD/CAM technologies use an intra-oral camera to capture images of the patient's dental arches. Images are processed and reconstructed by a manufacturer's software to form a 3-D dental model. From this point, the reconstructed digital files can be copied and stored on the personal computer or sent to distant servers. Although digital models can be produced in the office via this technique, the disadvantage is that the plaster casts cannot be produced using this current technology and must be processed by a company that can convert the digital model to another type of physical cast. If the operator needs to have the physical casts, the files need to be sent to a dental laboratory with the capabilitiy of fabricating the plastic stereolithographic models using 3-D printing technology. The disadvantages of this technique are the lab costs of fabricating the resin models and the processing time. Normally there is no shipping cost for sending digital files [37].

With the digital model technology, the clinician can enjoy the benefit of not having to support an in house lab with its concommittant mess. Because they are digital files, they can be saved onto personal computers or downloaded from the company website where access to these models is virtually anywhere at the click of a mouse. The biggest advantage of having digital dental models is the elimination of storage space [35]. A typical set of digital dental models can range from less than 1 megabyte to several megabytes depending on their pixel resolution. A portable thumb drive of 20 gigabytes usually costs less than 50 dollars and can hold approximately 24,000 sets of digital models [19]. With these numbers in mind, a portable 0.5x 2x3 inch-2 terabytes hard drive with a cost around 100 U.S. Dollars can store more than 1 million sets of models. As mentioned above, the files can be stored at a distant site and are available for download at any time, therefore, the dentist can use this service without having to buy a portable hard drive. Transporting the digital casts is virtually painless and does not incur any additional cost [41].

Since digital dental model systems are becoming more available, many researchers have measured the digital model for linear and volumetric accuracy to to gypsum base casts and finally to the patient. DeLong and coworkers compared measurements of the subjects to the plaster casts, and those of the digital models and determined that digital casts are clinically acceptable. And according to Santoro and coworkers, dimensional discrepancies between digital models and plaster casts are clinically insignificant [19, 39]. Fleming and coworkers performed a meta-analysis of digital models and reported that the overall mean dimensional difference between plaster casts and their digital models were minor and have no clinical significance [24]. Many other researches have also demonstrated the accuracy and clinical acceptability of digital dental models [20, 22, 25, 27, 32, 33, 38]

When utilizing digital models services offered by different companies, i.e. OrthoCAD™, dentists are not required to make any additional investment on the hardware and software beyond what is normally purchased to start a dental practice. The benefit of this technology is the relatively low cost of using this method which is approximately the same as the laboratory fee for a set of trimmed plaster models or the cost of storing the digital files which is negligible. Dentists who use CAD/CAM technology to acquire digital models in their office are generally spend between 50,000 to 130,000 U.S. Dollars for a portable computer and an intra-oral scanner. With the digital cast technology hopefully becoming more and more available to the dentist at a lower cost, many dental offices can purchase the scanning machine and the proprietary software to produce their own digital casts without the processing fees from traditional companies [18, 40].

There is no special training needed to gain competency for anyone who is not familiar with the software provided by companies who process these digital models.

The software is usually self-explanatory and anyone familiar with Invisalign can easily learn about digital models from its subsidiary company OrthoCAD™. However, these companies do provide technological support and training if desired. Currently, technology of digital dental models are heavily marketed to orthodontists. And over the last 15 years, many different manufacturers have been competing to develop and improve the computer hardware and software as well as make digital dental model technology commercially available and affordable to the average dental provider. Although this technology is promising, there are still many disadvantages that need improvement before any significant impact can be seen on the dental community at large [18,42].

Digital dental models and CBCT have evolved tremendously within the last decade and although they were designed as two separate entities we can combine the benefits of each technology and import the digital files of both the digital model and CBCT to create a new virtual model. Numerous studies in the past have shown that the reconstructed 3-D models of CBCT and digital dental models are dimensionally accurate and clinically acceptable. One must keep in mind that although each modality has its own limitations hopefully they are minimized when they are combined to form a new digital model [21, 28, 29, 39, 41,].

CBCT is an excellent tool for dentists to evaluate maxillary and mandibular bony structures, the 3-D root relationship to the bony housing as well as relationships of roots to vital structures such as paranasal sinuses and nerve bundles. Although CBCT cannot be used to capture and reconstruct the soft tissue tomography of the head and neck, its bony reconstructed model is great for surgeons to evaluate and treatment plan and perform virtual measurements for surgery. The 3D reconstructed images from CBCT and their stereolithographic models are not capable of delineating the intimate details of teeth such as ridges and fossa [19, 23]. Digital models on the other hand, are accurate 3-D replications of of teeth and soft tissue. With the understanding of the benefits of each and their limitations, it is therefore theoretically plausible to superimpose the two digital models to create one single accurate 3-D virtual representation of any patient. This union of images could conceivably be considered as a virtual patient base and offers many diagnostic and treatment planning advantages [21, 28, 29, 39].

The null hypothesis of this research study is: there is no statistically significant difference in the physical linear measurements made on a full size PVC skull replica compared to identical digital measurements made on a 3-D virtual reconstruction of the same skull and dental casts using scanned CBCT, digitized dental technology and computer imaging. The statistical significant level is chosen to be 0.05. If the p value is shown to be less than 0.05, then the null hypothesis is rejected.

MATERIALS AND METHODS

The following study was approved by the Womack Army Medical Center Institutional Review Board for Research, Fort Bragg, NC and by the Uniformed Services University of the Health Science, Bethesda, MD. Funding for this study was provided by the United States Army Dental Activity, Fort Bragg, NC, USA. No commercial/financial relationship, interest, or association that might pose a conflict of interest has been present.

DESIGN:

A human skull replica made of polyvinyl chloride (PVC) was used to test the accuracy of measurements of the physical model compared to measurements of the three-dimensional digital reconstructed superimposed model. The PVC model was selected due to its density and x-ray absorptive properties and anatomy similar to the adult human skull (figure 2). Linear measurements of the PVC model were made by selecting multiple fixed points on the occlusal and incisal surface of the maxillary teeth to the deepest point at the junction of the nasial and frontal bones. To facilitate this task, artificial notches were created by using a carbide disk to make 2-3mm wedge-shaped cuts on the incisal aspects of the maxillary anterior teeth number 6 to number 11, on the buccal cusp tips of teeth number 4, 5, 12, and 13, and on the occlusobuccal grooves on teeth number 2, 3, 14, and 15 (figure 2). The deepest point at the nasion was selected for this study because of its dimple shape and ease of identification in both the laboratory and on the CBCT reconstructed model. Furthermore, because the purpose of this study is to compare the accuracy of two 3D models, the reference points were carefully chosen to represent both models in a three-dimensional form.

On the PVC model, fifteen linear measurements were made from the most apical and outer aspect of the notches from tooth number 2 to tooth number 15 to the deepest part of the nasion dimple using a digital caliber (Salvin Dental Specialty) capable of measuring to the hundredth of a millimeter.

In the laboratory, three thin coats of a cast separator, Handler Slick-88 silicon spray, Handler Mfg., Co. Inc., Westfield, NJ, U.S.A., were sprayed to the maxillary teeth and the surrounding structures. Immediately after the model was sprayed with the separator, an impression of the maxilla was taken with irreversible hydrocolloid impression material, Jeltrate©, fast set, Dentsply, Detrey, Konstanz, Germany, using a stock tray previously sprayed with tray adhesive, Tray Adhesive Spray for Alginate, Henry Schein©, Henry Schein U.K. Holdings Ltd, Gillingham, United Kingdom.

Table 1.

Material	Water/Powder mL/g	Mixing Time (seconds)	Working Time (minutes)	Setting Time (minutes)	Optimal Temperature
Alginate	19mL/8g	45	1.5	2.5	73^{o}F

The water to powder ratio and mixing time of alginate were followed according to manufacturer's recommendations. Although water temperature affects the setting time of the alginate, it does not affect the accuracy of the dental casts. In this study, however, the water temperature was set at room temperature (72^{0} F) for consistency with the different trials. For this study, the impression material was hand mixed. After 1 minute of setting, the impression was separated from the PVC model and poured with dental type IV dental stone, Wip Mix, Louisville, KY, U.S.A., within 30 seconds of impression separation.

Table 2.

Stone Type	**ML water /100g powder**	**Mech. Mixing at 350-450 RPM**	**Working Time (minutes)**	**Setting Time (minutes)**	**Expansion %**
JADE STONE	22	20-30	5-7	10	.18

One hour after pouring, the cast was retrieved from the impression. The dental cast was then air-dried for at least twenty-four hours. Once the cast was dried and trimmed, it is then inspected for defects such as voids and blebs, especially on the notches, using a 10x microscope (Figure 3 and 4). Any void or stone blebs present on the most apical and outer aspect of the wedge-shaped notch that could affect the measurements will exclude the cast from the study and new impression will be made. Next, the cast was placed in the pre-calibrated Ortho 3-D Insight, Motion View Software, LLC, Carlsbad, CA, U.S.A. The scan was performed by following the manufacturer recommendation of securing the cast to the scanning platform with a double-sided adhesive tape. Using the software provided by Motion View Software, the cast was scanned and converted to a digital three-dimensional dental cast and saved for future use (Figure 5). This process was then repeated fourteen times.

Table 3. Ortho Insight 3D recommended exposure settings for dental stones.

Material	Type	Preview Exposure (second)	Scan Exposure (minute)
Gypsum	Dental Cast	70	2-3

Next, the PVC model was secured to the platform of the Kodak 9500 Cone Beam 3D System, Carestream Health, Inc., Toronto, Canada, with paper adhesive tape (Figure 6). In this step, two assumptions were made. First, because the reconstructed 3D image of the CBCT can be manipulated and rotated in any direction in space, therefore it is arguably valid to assume that as long as the model to be scanned does not move during scanning, mounting to exact orientation will have no effect on the accuracy of the produced reconstructed 3D digital model. Second, because the CBCT machine was calibrated and settings were pre-set by an experienced technician, plus, the scanning process does not involve any subjective intervention from the investigator, a total of fifteen scans can be performed consecutively with confidence of no variations between different scans. In this study, the parameters of the CBCT machine were set as follow:

Table 4. Manufacturer settings for Kodak 9500 Cone Beam 3D System.

Subject	kV	mA	S	Voxel	mGy·cm^2

Adult	90	10	10.80	300	1467

Upon completion of CBCT acquisitions, data was stored on the Womack Army Medical Center central server which can be accessed by any distant computer connected to this secure network. The desktop used for this study was an all-in-one Levono Enhanced Experience 2.0, Intel(RO) CoreTM i3 2120 CPU @ 3.30 GHz: 32-bit Operating System, Windows 7. The monitor resolution was 1600x900. By using the Dolphin Imaging software, Chatsworth, CA, U.S.A., which was pre-installed and pre-calibrated by certified technicians on our home clinic desktop, each CBCT file was imported into this program as a DICOM file. Once the CBCT image was imported into Dolphin Imaging software, the file is then reconstructed into a 3D model for further analysis (Figure 7). In the main menu, under implant functions, which enabled the digital dental cast to be imported onto the main screen (Figure 8). Superimposition is performed by positioning the alignment points matching both models. The Dolphin software was designed to have seven alignment points (Figure 9 and 10), however, in this study, only three points were used for models alignments.

With the reconstructed CBCT model and the digital dental cast arranged side by side, the alignment points were then meticulously placed in their desired positions, which were the most apical and outer point of the artificial wedge-shape cuts on teeth number 2, 9, and 15. This was done on both the digital dental cast and on the reconstructed CBCT images (Figure 11). Using the zoom and three-dimensional rotation functions, the alignment points on the digital dental cast were verified to be at the exact positions as those on the reconstructed 3D model. After this step was performed with the best judgment of the operator, the superimposition function would then allow the two images to merge and become one (Figure 12). The newly created 3D superimposed image then checked to make sure the two images were merged to our satisfaction by looking at the alignments on the surfaces of the anterior teeth (Figure 13).

Next, digital linear measurements were made in a similar manner to our measurements on the PVC model (Figure 14). Using the zoom out function, the software allowed the desired measuring points to be easily identified and adjusted. The study was repeated for the remaining fourteen trials.

STATISTICAL ANALYSIS

The student t-Test was used to compare the correlation of measurements of the two independent sets of data, measurements made on the PVC model and measurements made on the 3D CBCT/digital dental cast superimposition model. Due to the design of this study, fifteen measurements of the physical model was compared against the fifteen measurements of the virtual model for each tooth of the maxilla, from tooth number 2 to tooth number 15. Furthermore, a standard deviation calculation was also performed for each data set of each tooth.

Finally, for the purpose of expanding our sample size, the sum of all measurements of the PVC model for each tooth to nasion distant were compared to the sum of all measurements for each tooth of the superimposition model. By doing so, we increased our sample size from fifteen physical measurements to fifteen virtual measurements to 210 of each with all trials combined.

RESULTS

This study was to determine how well the two sets of data, one from the measurements on the PVC model and one on the digital reconstructed superimposed model, correlate to each other. With each tooth, tooth number 2 to number 15, measured from the occlusal/incisal scored notches to the fixed and deepest point located at the frontonasial fissure, two sets of data for each tooth were obtained. The numbers of repeated measurements equal the N value of 15. A mean value of each data set for each tooth was calculated. The standard of deviation was calculated for each tooth and finally, a Student t-Test was performed. To expand our sample size, all measurements from the PVC model was combined as one set of data and the same was done for all measurements of the virtual model. The same calculations were performed for the combined sets of data. All values were rounded to the nearest hundredth. The results are as follows:

Table 5

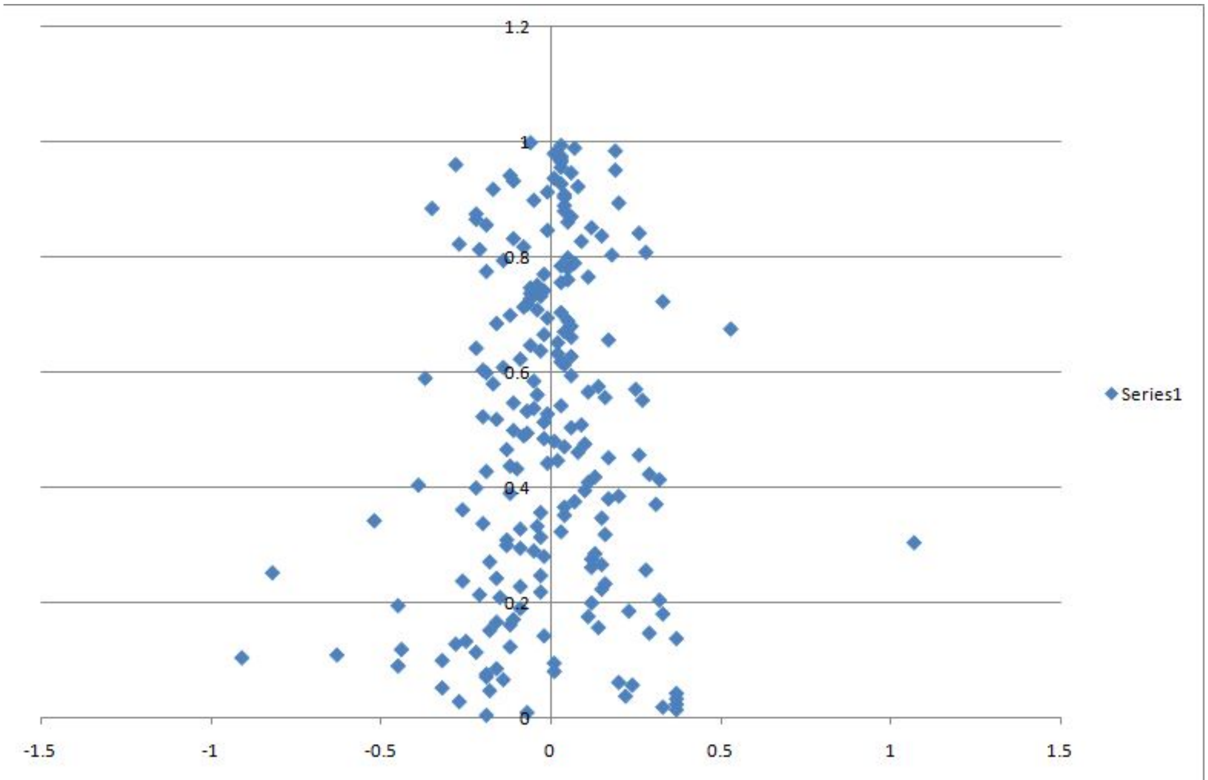
Tooth Number	Number of Trials (N)	Mean PVC Model	Mean Digital Model	Standard of Deviation PVC Model	Standard of Deviation Digital Model	Student t-Test
2-N	15	84.99	84.70	0.13	1.35	0.42
3-N	15	85.98	86.00	0.24	0.22	0.83
4-N	15	81.91	81.86	0.12	0.12	0.28
5-N	15	80.01	80.01	0.10	0.18	0.90
6-N	15	78.79	78.77	0.11	0.19	0.74

7-N	15	77.11	77.18	0.12	0.20	0.27
8-N	15	75.33	75.35	0.12	0.15	0.73
9-N	15	75.11	75.07	0.46	0.34	0.75
10-N	15	76.56	76.57	0.09	0.29	0.82
11-N	15	78.38	78.40	0.33	0.29	0.89
12-N	15	79.14	79.20	0.18	0.40	0.60
13-N	15	80.26	80.23	0.10	0.17	0.57
14-N	15	83.83	83.85	0.14	0.19	0.74
15-N	15	84.10	84.17	0.21	0.24	0.36

Table 6

Tooth Number	Number of Trials (Combine)	Mean PVC Model (Combine)	Mean Digital Model (Combine)	Standard of Deviation PVC Model (Combine)	Standard of Deviation Digital Model	Student t-Test
2-15	15	1121.49	1121.66	1.05	1.39	0.71

Figure 1. Distributions of linear variations between PVC and digital models



Distribution curve of value differences between PVC and 3D superimposed model

In our experiment, the differences in linear measurements ranged from 0.01 mm to 1. 07 mm, with 97.14% of data fell within ±0.5 mm and 75.24% of data fell within ± 0.2 mm. When the data was analyzed individually, that is one set of linear PVC measurements compared to one set of linear digital measurements of the superimposed model, all of the Student t-test values were much greater than p-value of 0.05. This strongly indicated that there is no statistical significant difference between the two models. To further test our null hypothesis, all measurements of the PVC model were collectively treated as one set of data, this is then compared to all measurements of the superimposed model combined together, the value of the Student t-Test was 0.705678 which is a lot larger than the p-value of 0.05. With a combined data set of 210 values for both the PVC and the superimposed model, the Student t-Test strongly indicates that there is no statistical significant difference between the two models.

DISCUSSION

The capability of merging two digital images to produce one single 3-D reconstructive model that can accurately represent a dental patient would undoubtedly have a tremendous impact of diagnosis and treatment planning in the near future.

Since CBCT technologies were made commercially available to the dental practitioner they were being used primarily for diagnostic purposes. The capability of of a reconstructed CBCT enabling dentists to view and manipulate the facial complex has had added tremendous diagnostic value to patient care and treatment. Furthermore, multiple researchers have concluded that there is no clinically significant difference between a calibrated reconstructed CBCT 3-D image and the actual patient. This also holds true with the 3-D digital dental cast. There are many added benefits of each technology, yet individually each can only benefit to a certain extent but merging these two technologies to produce a composite 3-D digital model will certainly represent the dental patient more accurately without his or her physical presence in the dental office. With this new frontier in digital technology, the benefits, for both the dental providers and patients can be numerous. Patterson Technology is among the leading software companies offering a software called Dolphin that is capable of creating a 3-D digital superimposed model composed of a reconstructed CBCT image and a digital dental cast. As a result, this study was designed to test the accuracy of a superimposed 3-D digital model and its digitized dental models to the physical model composed of a PVC skull and stone dental casts.

As mentioned above, many previous studies have concluded that reconstructed 3-D images taken by any CBCT technology, and digital dental casts have shown dimensional accuracy between patients' bony architecture of the craniofacial complex and to the patients' dentition respectively. In this study, however, it is important to point out that several assumptions were made which may have contributed to variations in data collection.

First, the digital caliber used for this study was equipped with a calibration button which prior to taking the first measurement of the PVC model, it was calibrated to 0.00 mm once and no further calibration was made thereafter. This assumption is justifiable because all measurements were made of the same PVC model therefore it is reasonable to believe that any calibration between trials might introduce inconsistencies of measurements from one trial to the next. By calibrating it only once, we assumed that all measurements will be the same and if there are variations, they could be the results of other parameters in our study. Although this argument is sound, there is no way to confirm our assumption therefore, one must accept the contrary argument that there might a certain degree of inherent inconsistency by calibrating this device only once and not before each successive measurement. It has not been determined if this could cause any variation in data collection.

Second, according to Nassar, irreversible hydrocolloid has an inherent dimensional change ranging from 0% to 0.32% when instructions provided by the manufacturer were strictly followed [43].

Third, the dental stone used in this study was type IV and when carefully following manufacturer directions, it was expected that the final dental cast will have a volumetric expansion of 0.18% as this is a well-known fact and was confirmed by numerous dental literature. Current technologies with capabilities to create 3D digital superimposition of CBCT and digital dental cast appear to assume that this volumetric expansion of type IV dental stone has no clinically significant impact in the overall dimension of the superimposed reconstructed 3-D model. In this study, however, because measurements of the digital model were made in the tenth of a millimeter it is recognized that such inherent material expansion could be a factor affecting the measurements.

Fourth, this study utilized the Ortho 3-D Insight to scan the dental casts and convert them into the 3-D digital casts. The reconstructed 3-D images of the PVC skull replica were obtained by the Kodak 9500 Cone Beam 3-D System. After the reconstructed 3-D CBCT and digital dental cast images were obtained, they were imported into Dolphin for superimposition. Although, each of these machines and software were pre-calibrated by certified technicians, this study did not take into account the possibility of any inherent inaccuracy with each technology. According to past studies, the reconstructed 3-D CBCT images have a ± 0.2 mm dimensional inaccuracy when compared to measured subjects. Similarly, many previous studies conclude that the digital dental casts have a ±0.02 mm when compared to physical dental casts.

In this study, accuracy was measured based on two sets of values, namely, one on the PVC skull replica and one on the final reconstructed 3D superimposition model. By doing so, we assumed that the different steps involved and the different technologies had no effect on the measurements of the final reconstructed 3D superimposed images, or at least, their inherent errors have no statistical significance when compared to those measurements of the PVC model. Furthermore, ignoring such potential errors could make it almost impossible to identify the source causing incorrect measurements if any.

With the above assumptions as the independent variables in this study, it is valid to argue that errors in any of the steps can result in different measurements of the virtual model as compared to the PVC model. The additive effects can result in greater differences or they could also offset each other and result in measurements closer to the physical measurements. Although past studies have concluded that each of the independent variables by itself has no clinical significance we can only assume that the errors contributed by these independent variables had no effect on the outcome of this study. Aside from the independent variables, it is extremely important to notice that the measurements on the PVC model and on the virtual model were solely based on the skills of the operator. There is no doubt that human error could be the most important single factor affecting the overall accuracy of the virtual model compared to the physical PVC model.

First, by analyzing the data from different trials and measuring the same parameters on the PVC model, one can clearly see that they were not the same. For example, the linear measurements of tooth number 8 had a difference ranging from – 0.32 mm to 0.37mm and this is also true for all other measurements. Because the digital caliber was calibrated, it is reasonable to conclude that the different measurements were the result of the operator's inability to accurately repeat the intended positions of measurements. Secondly, after the 3-D reconstructed models and the digital dental casts were imported into Dolphin, superimposing the two images together relied exclusively on the ability of the operator to correctly match the positions of the realignment dots to each other. This step was more or less, a "guessing" game. If measurements were made in centimeters, this matching of realignment dots might not negatively affect the results. However, because measurements in this study were made in the tenth and hundredth of a millimeter, incorrect matching of realignment dots could result in a significant difference clinically.

The results of this study suggest that current technologies in creating a 3-D virtual patient from the DICOM files of a CBCT and digital dental casts is clinically acceptable and have the potential for many applications. The disadvantage of creating a virtual model with today's technologies, however, remains a cumbersome task for the dentist due to the multiple steps involved. Besides the labor involved in producing a virtual model, there is no doubt that each of the steps involved has the overall potential to introduce error into the final result.

CONCLUSION

In our study the accuracy between the physical model and the constructed CBCT/digital dental cast superimposition were supported by all calculations of the Student t-Test for each individual tooth and its resulting p-value. From the analysis of this study, it can be inferred that the differences in linear measurements were not statistically significant and are therefore identical. This gives us confidence to create a virtual three-dimensional model that is dimensionally accurate to the physical patient. We can accurately make measurements on the 3-D model that can accurately translate to the patient.

As digital technologies used in dentistry are being developed at a faster pace, it is obvious that our virtual patient concept will not only replace our conventional approach to patient diagnosis and treatment but has the potential to surpass our current level of diagnostic capability and increase the level of patient care in the future. Its usefulness will encompass all clinicians, however, certain specialties will benefit more than others depending on the types of treatments provided by each. Further research is recommended. 1) To include more alignment points and test whether it will increase the accuracy of the virtual model as compared to the physical model. 2) This technique to create virtual digital model relies heavily on the skills of the operator, therefore, by employing technologies capable of digitally aligning models, this will theoretically eliminate the majority of human errors. One possible alternative is to integrate CAD/CAM technology with greater CBCT technology in the future.

APPENDIX: PHOTOGRAPHS

Figure 2. Image of the PVC skull replica scored with carbide disk on the incisal aspects of anterior teeth and occlusobuccal aspects of posterior teeth.

Figure 3. Image of dental cast with scored marking on anterior teeth.

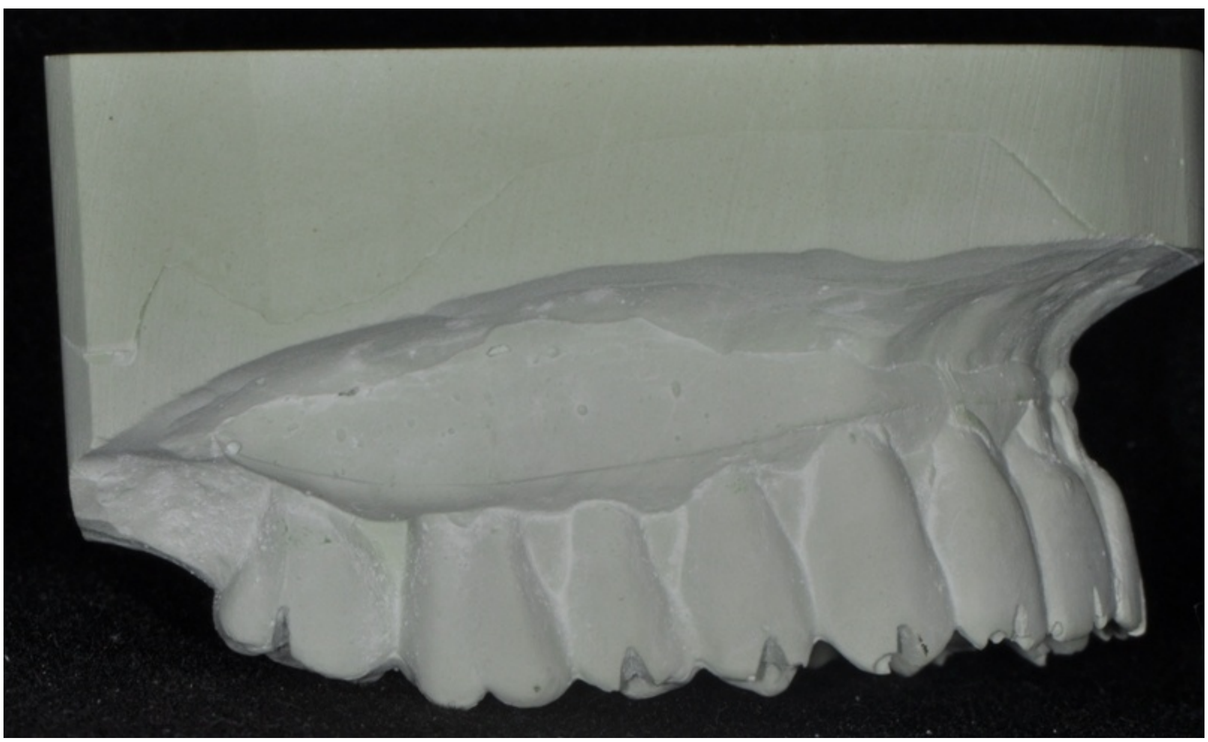


Figure 4. Image of dental cast with scored markings on posterior teeth.

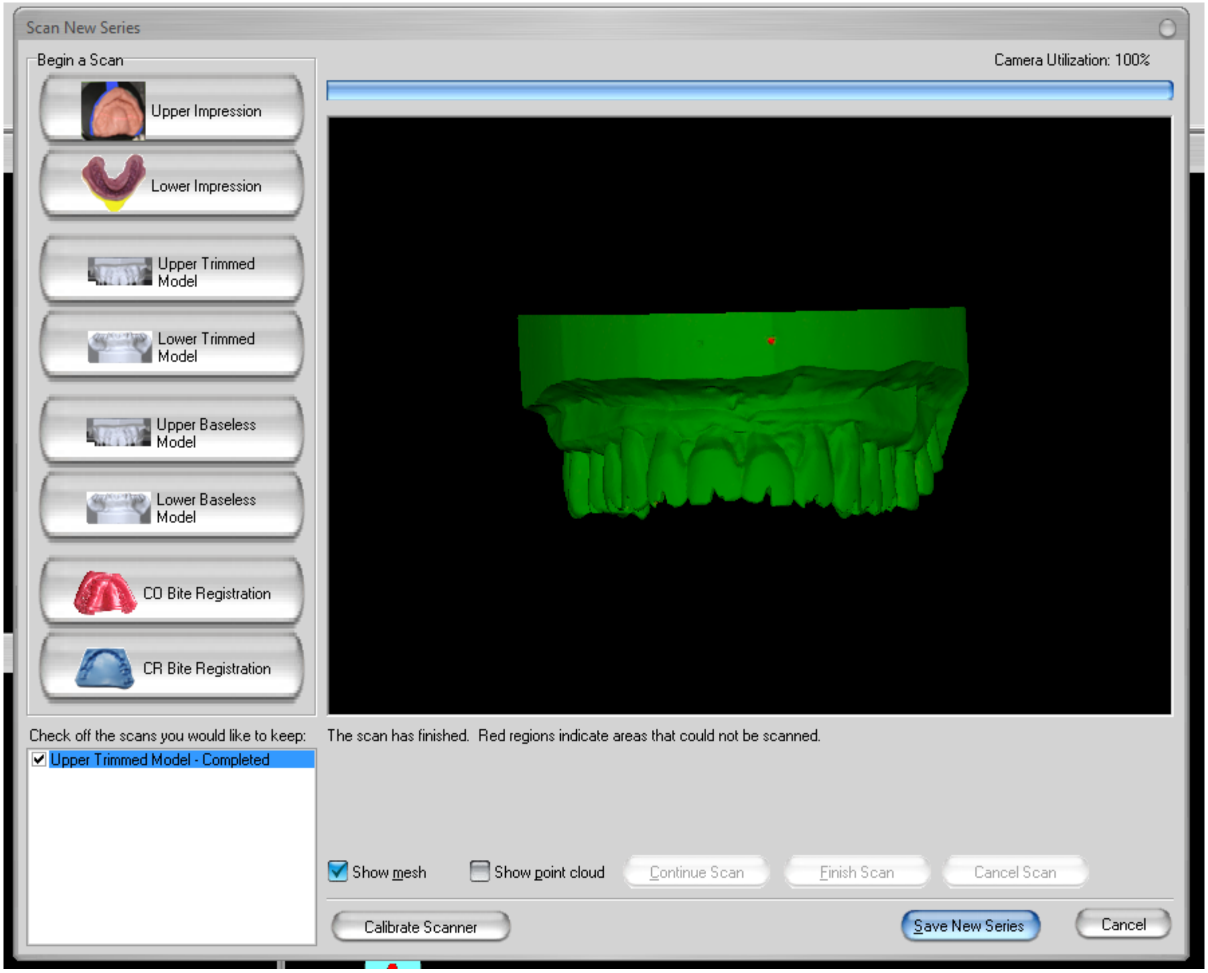


Figure 5. Image of digital dental model made using the Ortho 3D Insight scan and software.

Figure 6. PVC model was mounted in similar fashion as actual patient during CBCT acquisition. Model was secured with adhesive tape.

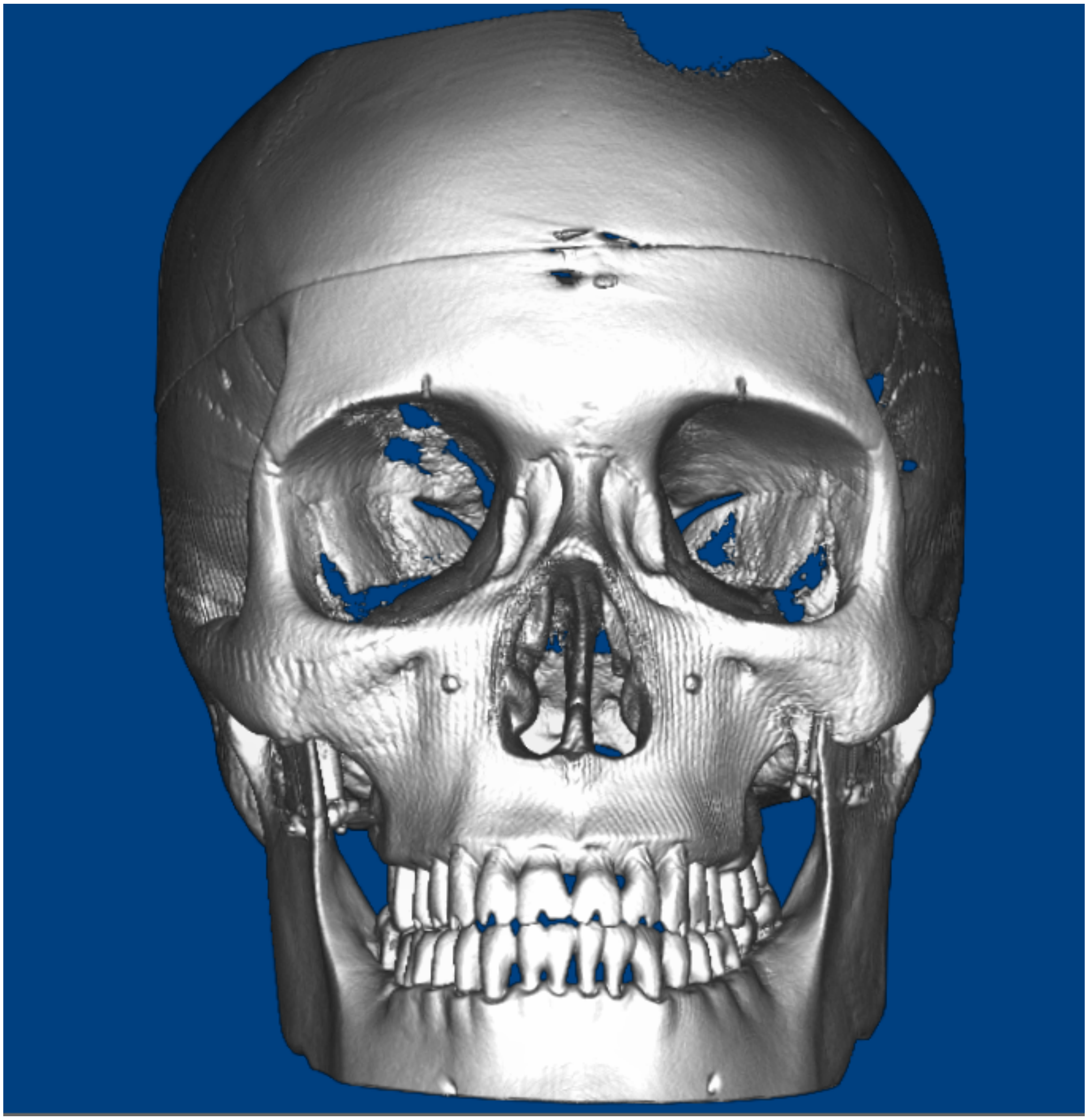


Figure 7. Screen image of the reconstructed 3D CBCT model in Dolphin Imaging software.

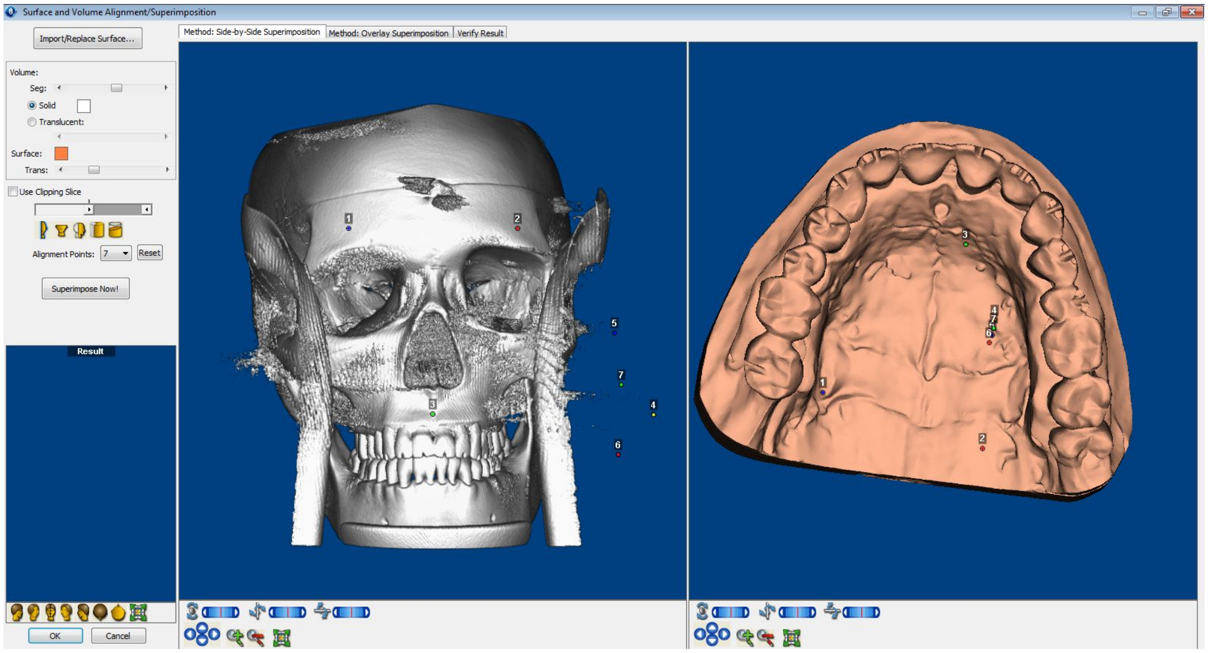
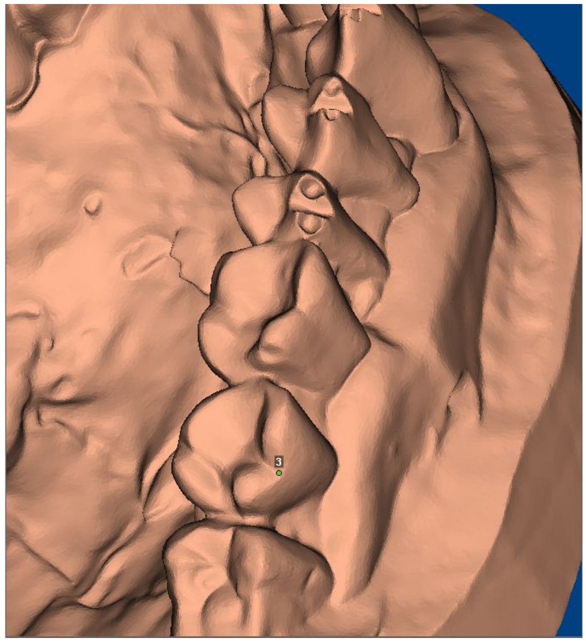


Figure 8. Screen image displaying the reconstructed 3D CBCT and the digital dental cast side by side after imported. It also showed the different alignment points oriented in space numbered from 1 to 8 on each model. Only 3 alignment points number 1 to 3 on each model were used for this study.



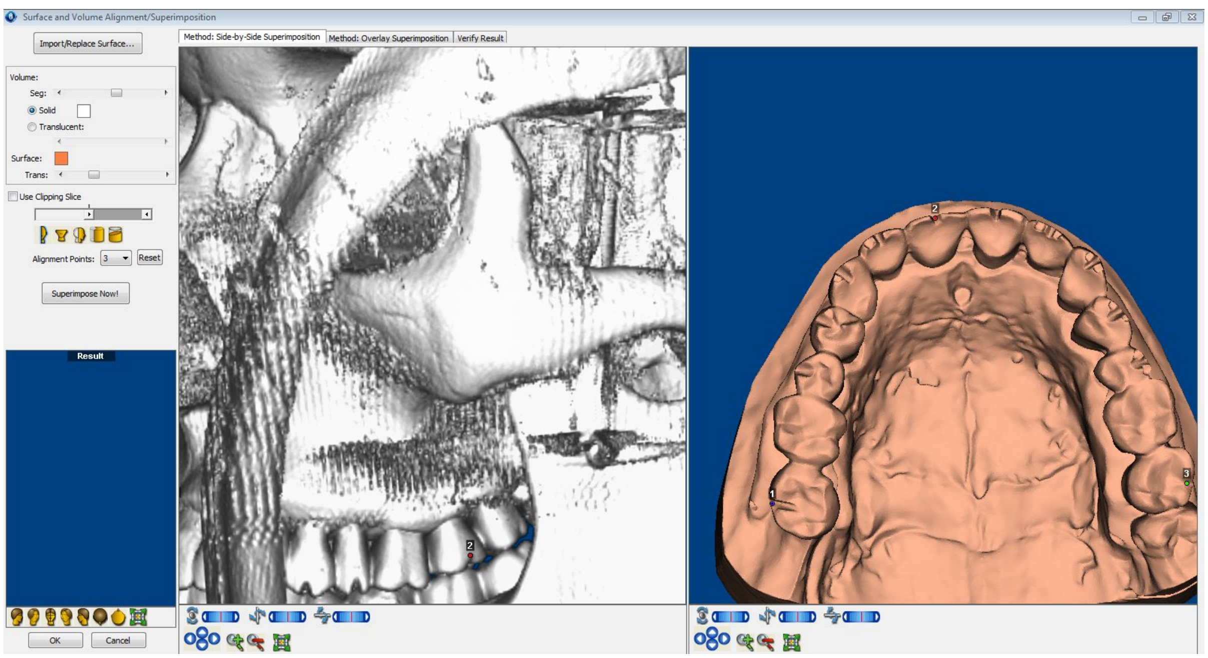


Figure 9 and 10. Alignment points are placed on the scored markings of tooth number 2, 8, and 15. The points are numbered 1, 2, and 3 for both models.

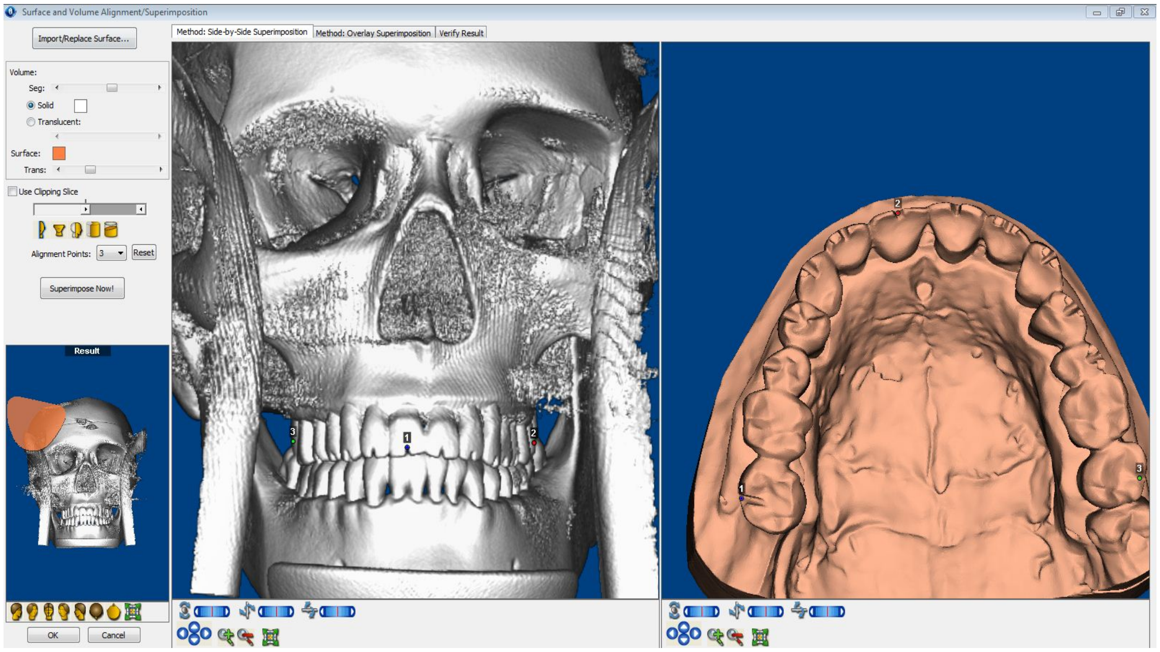


Figure 11. Both models are verified to have proper and matching alignment points.

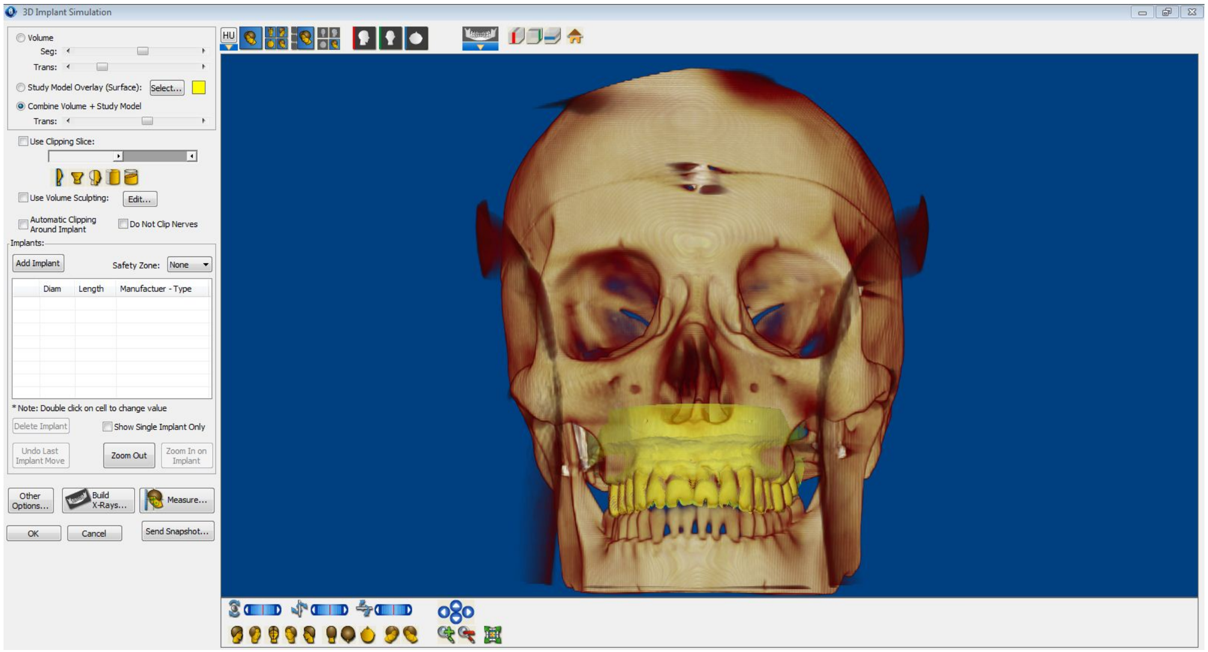


Figure 12. Screen image displaying frontal view of the superimposed 3D model.

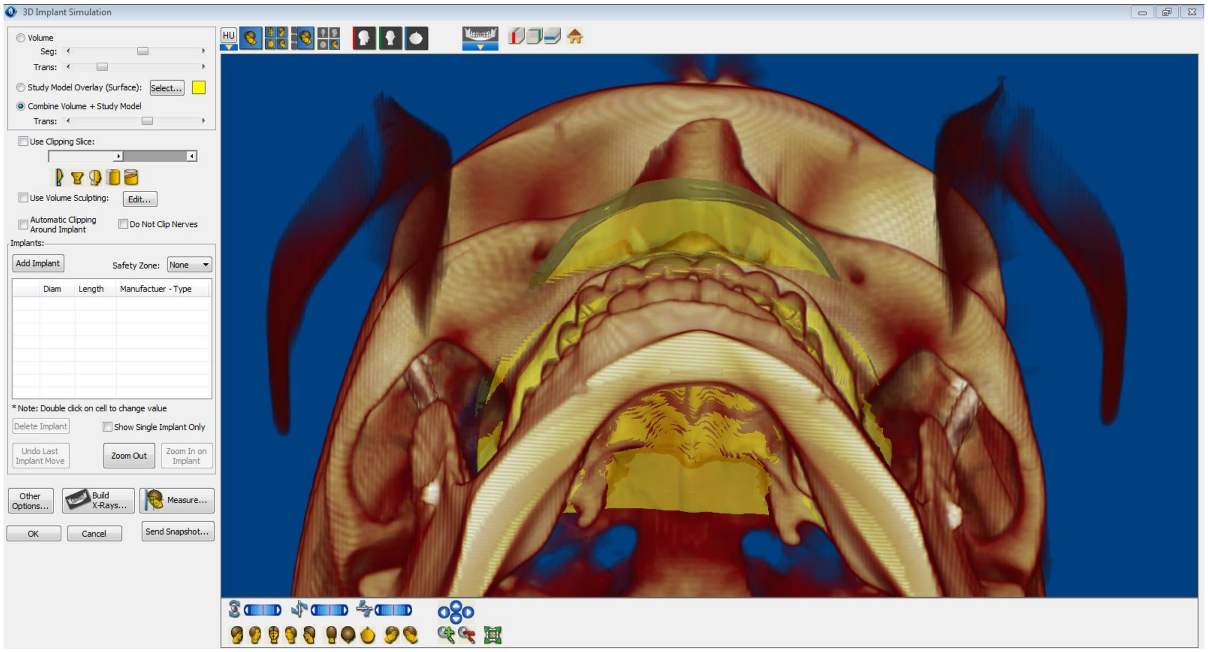


Figure 13. The superimposed model was check for alignment.

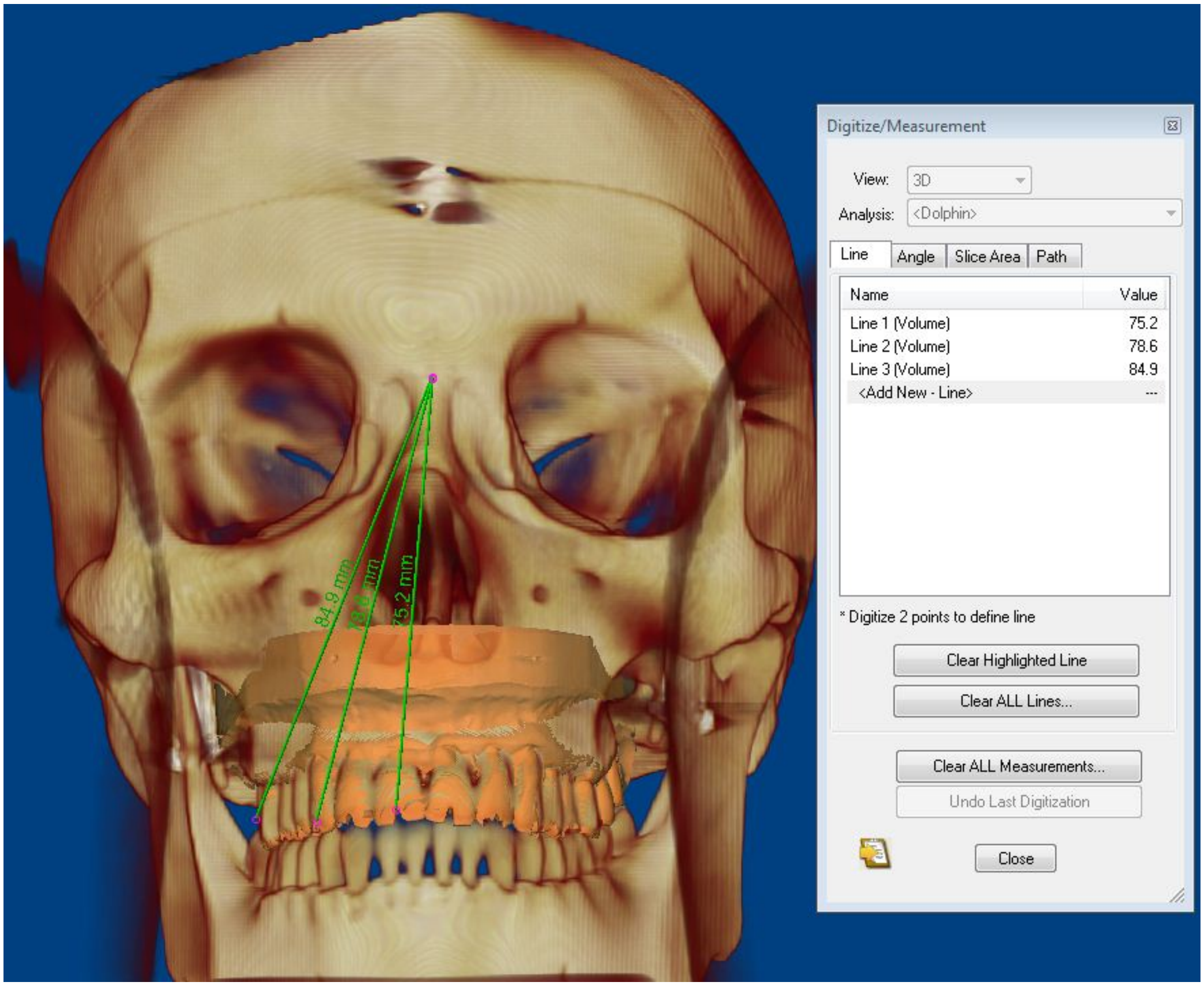


Figure 14. Linear measurements were made from the scored markings to the deepest point at the junction of the nasial and frontal bones.