Comparison of CT and CBCT for fabrication of dentistry models via rapid prototyping technology

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ABSTRACT: Medical models may be fabricated using rapid prototyping (RP) technologies, which the 3D data are provided via medical imaging technologies. Physical models provide for surgeons a direct, intuitive understanding of complex anatomic details which otherwise cannot be obtained from imaging on screen. The first step in fabrication of physical models using rapid prototyping (RP) is to acquire the data for the existing structure of interest. Thus image quality is very important in data acquisition, because an invisible image makes problem in data acquisition, and consequently influences the data processing and model fabrication as well. Therefore this paper compares the quality of data acquired via CT and CBCT for the purpose of physical model construction using rapid prototyping (RP) technologies.

Keywords: Rapid Prototyping; CT; CBCT

1 INTRODUCTION

Medical imaging technologies involve from X- ray radiology to more advanced and refined medical imaging modalities such as CT, CBCT, MRI and laser digitizing (Colin et al. 1997). These new technologies are able to provide detailed three-dimensional pictures of the anatomy of the area of interest and therefore valuable data for diagnostic and therapeutic usage (Diamantopoulos et al. 2002). Techniques have been developed, together with software and hardware, to represent the data in 3D on a 2D screen. Given the visualization provided by sophisticated software packages, the fabrication of physical models may seem superfluous.

However, the display of a 3D volume on a 2D screen does not provide surgeons with a complete understanding of the patient's anatomy. Surgeons must learn to interpret the visual information in order to reconstruct mentally the 3D anatomical geometries. Recently, head-mounted displays, stereoscopic glasses, and holograms have been employed to complement the 2D screen to provide more realistic representations of 3D volume models. Unfortunately, there is still no physical feel of the area of interest, like the infection area or fracture size, until an operation is performed (Chelule et al. 2000). In short, there are several visualization issues that are being addressed but not yet resolved by virtual models.

Therefore this makes the construction of physical models often necessary. Physical models are attractive to surgeons because they offer the opportunity to hold the model in hand and view in a natural fashion, thus providing surgeons a direct, intuitive understanding of complex anatomic details which otherwise cannot be obtained from imaging on screen. The use of physical models also creates improved prerequisites for planning and simulation of complex surgery.

With a physical model at hand, a surgeon is able to exercise on the model with the usual surgical tools, enabling him/her to rehearse different surgical plans realistically. Based on this, surgery can be simulated in a way that is not possible even with the latest visualization technologies. Such an intensive planning of surgical procedures allows the selection of the best technical approach. Additionally, the communication between the surgeon and the patient before a complicated surgical procedure can be clearly improved by the use of physical models (Petzold et al. 1999).

2 FABRICATION METHODS OF PHYSICAL MODELS

A physical model can be manufactured based on X-ray, CT or MRI data. Several methods can be employed to fabricate a physical prototype. These methods can be divided into two categories: subtractive and additive. They all start with a 3D computer aided design (CAD) model of the anatomical area, which usually can be derived from X-ray, CT, CBCT or MRI data. The subtractive technique used is the conventional numerically controlled (NC) machining, generally milling (Petzold et al. 1999). In this case the shape of the model is milled from a block of polyurethane or other foam. The advantages include low material costs and the possibility that these models can be worked on with surgical instruments.

This method has two limitations. One limitation results from milling machines, which have restricted motion capability. Complex geometries are difficult to program and can result in tool/work piece collisions, and they are often the cases in medical application (Potamianos et al. 1998). The other limitation lies in the materials used to fabricate the physical model. The materials employed should be hard, tough, and sterilizable.

Klein employed polyurethane foam to fabricate the milled model in pediatric craniofacial surgery (Klein et al. 1992). Quality of the milled models was limited because the polyurethane foam is brittle and soft and the material is not sterilizable. Therefore, additive methods are advantageous to fabricate the physical models of anatomical details. The main advantage of RP is that medical models can be created that have undercuts, voids, and complex internal geometries such as neurovascular canals or sinuses. They can also be translucent and the internal geometries can be easily seen. The main problems with milling includes: difficulty with small geometries, complex shapes, fixturing, and not having access to undercuts.

Rapid prototyping (RP) refers to the fabrication of 3D physical models directly from a computer-aided design model (Cooper 2001). The model is built layer by layer according to 3D data. In comparison to subtractive technology, the additive technologies can produce arbitrarily complex structures and cavities. Common RP technologies used in medicine are selective laser sintering (SLS), fused deposition modeling (FDM), stereolithography (SLA), and inkjet based system. The materials that can be used are fairly diverse. One can always find suitable material for his/her specific purpose. RP technologies have been successfully employed to reduce production time and build complex models which are otherwise difficult to make by the conventional NC machining process.

The use of RP to conceptualize complex functional models is emerging as a communication system to keep the client involved in every step of the product evolution process. Not only can these models improve the accuracy of diagnosis and surgical planning, but can also provide a route for manufacturing and validating customized implants (Amethyst. 2005). Quality of design and whether products are being developed to fulfill client's needs, or whether it is merely an over-the-wall practice is a constant debate (Groover. 1996). RP is changing this, whereby physical models, exactly representing the design, allow for communication with all stakeholders involved in the product. This is vital in the medical field, enabling surgeons to discuss planned interventions with patients, medical insurance schemes, etc. It also allows for preparatory work to be done, with shortened theatre operation times as a result, which in essence accelerates the surgeon's production development time resulting in huge cost savings (Amethyst 2005).

However, working with RP technologies in the medical field differs radically from using them in the manufacturing environment. In manufacturing, models are usually designed on the computer screen, then converted to physical models. In medical applications, the object or part often exists physically. Building medical models essentially starts with acquiring data such as computed tomography (CT) cross sectional images. Prior to part building, this highly complex data needs to be preprocessed to provide a format that a CAD package or a RP system can recognize. It can be seen that data scanning and processing technologies must be linked with RP technologies to obtain the desired high quality physical models. The data has to undergo a number of processes: data acquisition, image processing and model fabrication.

RP technologies are playing a more and more important role in medicine. The main advantages of RP technologies are reduced operating time and improved implant conformity, which lead to a greater quality of implant, reduced mortality rates, greater patient satisfaction, and a lower cost of treatment in the long term. It becomes a common practice to fabricate RP physical models from scanned data during the diagnostic and therapeutic periods.

3 TYPICAL RAPID PROTOTYPING SYSTEMS

A dental model is very difficult to fabricate using the conventional subtracting method because of its complexity. Rapid prototyping (RP), also called layered manufacturing or solid freeform fabrication (SFF), is becoming more attractive in dental

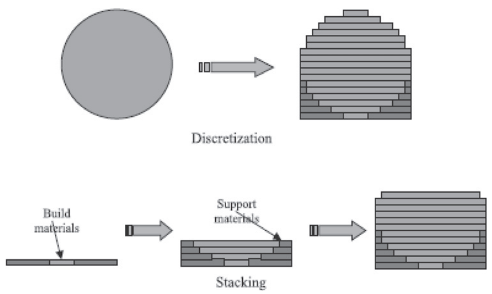


Figure 1. Principle of rapid prototyping.

applications. The basic concept of rapid prototyping is discretization and sequential stacking, as shown in Figure 1. By discretization, a complex 3D building problem can be changed into a simpler 2D layer building problem without part complexity limitation. By sequential stacking, building material is precisely deposited in a pre-determined order to form the desired 3D dental model. If a model has features like overhang or undercut as shown in Figure 1, then support layers are needed to support the build material. Otherwise, the build material will collapse. For certain RP systems, no separate support material is needed because the build material itself can also be the support material.

All rapid prototyping processes start from a 3D CAD model which can be derived from other CAD packages or scanned data. The model is sliced into multiple layers along one direction (usually Z direction) with a pre-determined layer thickness. Each layer contains information of model contours and interior fillings of the model at that height. Then the layer information is used to generate machine control codes and sent to a rapid prototyping system to direct the nozzle or laser beam to fabricate each layer of the physical model. The physical model is built in a layer by-layer manner, with each layer firmly stuck to the previous one. For some processes, post-processing is needed.

4 FABRICATION OF RP MODELS BASED ON MEDICAL DATA

The reported medical applications of RP technologies can be classified to the following categories:

- Biomodelling, which involves the fabrication of physical models of the human anatomy and biological structures in general, for surgery planning or testing.
- Design and fabrication of customized implants for prosthetic operations, rehabilitation, and plastic surgery.
- Fabrication of porous implants (scaffolds) and tissue engineering.
- Fabrication of specific surgical aids and tools.
- Drug delivery and micro-scale medical devices.

One of the major medical applications of RP is the fabrication of human anatomy models of a patient based on data obtained through the various well-established techniques of CT or MRI (Galantucci et al. 2006). The fabrication process of these physical models, which are nowadays often called biomodels, involves three phases (Petzold et al. 1999):

- The first step is to obtain the data of the patient's area of interest with the use of the previously mentioned techniques (CT, CBCT, MRI, etc.), which provides an indirect representation of the patient's anatomy through a series (stack) of 2D images.
- The images are next manipulated employing special software, which facilitate the separation and highlighting of the interested tissues (soft or hard) that represent the area of the biomodel, and allow the conversion of the 2D image information to a 3D representation. Usually, the standard STL representation is utilized for the latter.
- Finally, the biomodel is fabricated via an RP system followed by manual finishing (if it is necessary).

The accuracy of RP biomodels depends on various factors associated with all phases of the process. Choi analyzed the possible sources of error in SL biomodeling and dentified the main sources of error in the second phase, namely, the translation of 2D data to a 3D virtual model (Choi et al. 2002). This has led to the development of special software tools like Mimics from Materialise Inc. and Biobuild Inc. that have simplified and enhanced the accuracy of the 2D-3D data transformation process. Regarding the manufacturing accuracy of RP technologies, Santler concluded that it is sufficient for clinical purposes (Santler et al.1998).

5 DATA ACQUISITION

As mentioned before, an object or part of the object exists physically in dental applications, so the first step is to acquire the data for the existing structure of interest. Contact and non-contact methods can be used for data acquisition. Only non-contact methods are considered here. The most common techniques used in acquiring detailed anatomical information are computerized tomography (CT), cone-beam computed tomography (CBCT), magnetic resonance imaging (MRI), and laser digitizing. Other techniques include ultrasound, mammography, and X-ray.

5.1 *Computerized Tomography (CT)*

CT is a radiographic technique for producing cross-sectional images by scanning a slice of tissue from multiple directions using a narrow fan X-ray beam. The absorption of each tissue element is calculated and the result is displayed as a gray-scale image on a video monitor. The basic principle of CT scanning is that the internal structure of an object can be reconstructed from multiple projections of that object (Maher 2002, McAloon 1997 & Lightman et al. 1994).

A standard CT scanner operates by collecting information in one plane (slice) at a time. As shown in Figure 2, the X-ray transmission is measured along the detector array completely encompassing the patient. The detector array has typically 512 or 1024 elements. CT uses radiation in the form of a highly collimated X-ray fan beam to slice a two-dimensional image or slice plane. An X-ray tube and a detector array travel on a circular path around the patient collecting a complete set of data over 360°, thereafter, the respective image is constructed and the patient is moved a small distance through the gantry for the next transverse section to be measured. Figure 3 shows a typical CT apparatus.

The process is repeated at a sufficient number of views to permit mathematical reconstruction of the X-ray density at all patient locations intersected by the plane of observation. Scans are also needed above and below the region of interest in order to provide the reconstruction algorithm with sufficient boundary information. The density ascribed to the specified spatial location at the geometric center of the voxel is actually the average density within the voxel. The slice data can then be displayed in a stacked configuration, providing a "3D" presentation based on volume rendering.

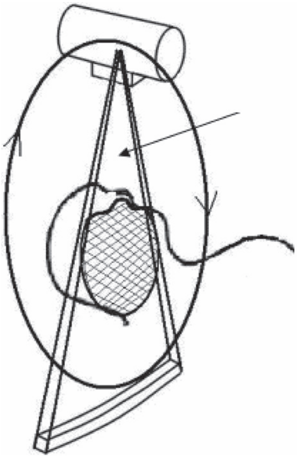


Figure 2. Schematic of a CT scanner.

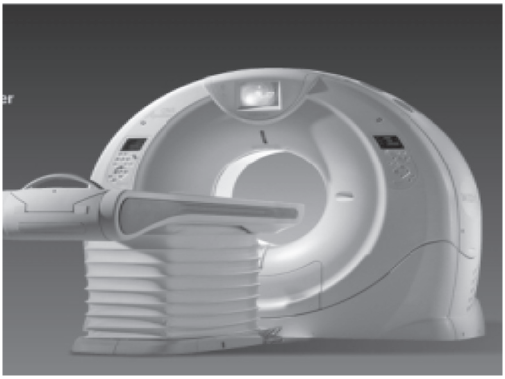


Figure 3. A typical CT apparatus.

In-plane resolution is determined by the aperture of the detector elements, which is related to the number of detectors used. The depth resolution is determined by the apertures of the X-ray source and the detector adjusted to meet the needs of collecting sufficient signals within safe exposure limits. The high-resolution scanners have instrumental functions of 3 × 3 mm (in the plane) and 2–10 mm (or larger) along the axis. In many cases, the scanned data lacks development of the surface structure necessary to define the true 3D surface because of the lower depth resolution. Therefore, post-processing of the scanned data is needed. The quality of the finished model varies directly with the accuracy of the machine and the resolution of the data.

Resolution can be increased by decreasing slice thickness, producing more slices along the same scanned region. The longer scanning period required for a high resolution scan must be weighed against increasing the patient's exposure to radiation, scan time and cost, and patient discomfort. Fortunately, new spiral CT scanning technology allows faster acquisition and smaller slice intervals compared to traditional scanners that must translate the patient for each transverse section. The spiral CT is based on the continuously rotating CT measurement systems. Sliprings are adopted to transfer the necessary electrical energy to the rotating gantry part and to transmit the measured data from the rotating part to the computer system, while the cables are used in the conventional CT scanner.

In spiral CT the patient is translated continuously through the gantry while the X-ray tube and detector system rotate around the patient with data being acquired continuously. Relative to the patient, the focus of the X-ray tube describes a spiral path. Therefore, this scanning procedure is called spiral CT or helical CT. In spiral CT, the images can be reconstructed at any position within the volume, even overlapping with the positions chosen retrospectively and without the need for renewed scanning. Furthermore, the depth resolution along the longitudinal axis is improved because of continuous scanning. Resolution of approximately 1 mm can be achieved in most practical situations.

5.2 *Cone-Beam Computed Tomography (CBCT)*

Cone-Beam Computed Tomography (CBCT) is a recent technology initially developed for angiography in 1982 and subsequently applied to maxillofacial imaging (Fig. 4). It uses a divergent or cone-shaped source of ionizing radiation and a two dimensional area detector fixed on a rotating gantry to acquire multiple sequential projection images in one complete scan around the area of interest. It is only since the late 1990s that it has become possible to produce clinical systems that are both inexpensive and small enough to be used in the dental office (Withe 2009).

Four technologic factors have converged to make this possible: (1) the development of compact high-quality flat-panel detector arrays, (2) reductions in the cost of computers capable of image reconstruction, (3) development of inexpensive X-ray tubes capable of continuous exposure and, (4) limited-volume scanning (e.g., head and neck), eliminating the need for sub second gantry rotation speeds.

Cone-beam scanners use a two dimensional digital array providing an area detector rather than a linear detector as CT does. This is combined with a three dimensional (3D) X-ray beam with circular collimation so that the resultant beam is in the shape of a cone, hence the name "cone beam". Because the exposure incorporates the entire region of interest (ROI) only one rotational scan of the gantry is necessary to acquire enough data for image reconstruction. Cone beam geometry has inherent quickness in volumetric data acquisition and therefore the potential for significant cost saving compared with CT. CBCT produces an entire volumetric data set from which the voxels are extracted. Voxel dimensions are dependent on the pixel size on the area detector. Therefore CBCT units in general provide voxel resolutions that are isotropic-equal in all three dimensions.

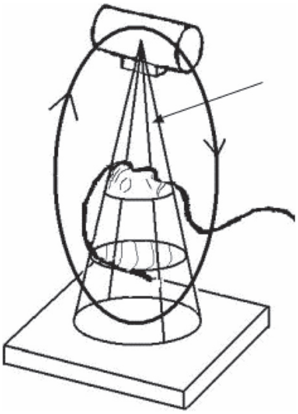


Figure 4. Schematic of a CBCT scanner.

The voxel size with which projection images are acquired varies from manufacturer to manufacturer principally on the basis of the matrix size of the detector and projection geometry. In addition, CBCT units may offer a selection of voxel sizes. For these choices the image detector collects information over a series of pixels in the horizontal and vertical directions and averages the data. This collation or pixel binning results in a substantial reduction in data processing, reducing secondary reconstruction times therefore, voxel size should be specified as either acquisition or reconstruction. Generally, decreasing voxel size increase spatial resolution, but because of the pixel fill factor of a particular flat panel a higher radiation dose may be required.

Currently, all CBCT units use mega pixel solid-state devices for X-ray detection. These devices provide sub millimeter pixel resolution of component basis projection images. CBCT produce images with sub millimeter voxel resolution ranging from 0.4 mm to as low as 0.125 mm. Because of these characteristic, coronal and subsequent MPR of CBCT data has the same resolution as axial data. This level of spatial resolution is applicable for maxillofacial application.

CBCT specific applications in dentistry include implant site assessment, localization of inferior alveolar canal, temporal mandibles joint, construction of the maxillofacial complex, and in rapid prototyping. CBCT imaging systems have been recently been introduced for imaging hard tissues of the maxillofacial region. CBCT is capable of producing accurate, sub millimeter resolution images at shorter scan times, lower dose, and lower costs compared with medical fan-beam CT. Increasing availability of this technology provides the practitioner with an images modality capable of providing a 3D representative that is extending maxillofacial imaging from diagnosis to image guidance of operative and surgical procedures. Figure 5 shows a typical CBCT apparatus.

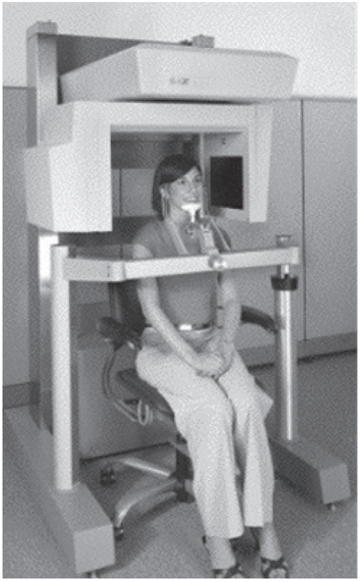


Figure 5. A typical CBCT apparatus.

6 DATA PROCESSING VIA MIMICS

At first CT and CBCT images must be at the DICOM format. Once the CT or CBCT images were imported into Mimics, the first step was to adjust the contrast for easy viewing, followed by selection of an appropriate threshold value for the region growing function. To select an appropriate threshold, the profile line function was used, which measures the density of the tissue along a user-defined line based on the grayscale values (Figs. 7 and 11). The selection of the threshold value is crucial for the accuracy of the resulting model. If the value is selected too low, then the resulting model will be smaller than the actual mandible, and vice versa. The threshold function will separate the soft tissue from the hard tissue isolating the bone structure only.

To complete the isolation of the hard tissue, the region growing function was used. This function connects all volumetric pixels (voxels) within the threshold that are physically connected to the initially selected voxel. Multiple region growing were applied using different masks and colors. Each mask was converted into a 3D model using the "*calculate 3D*" function. Because of the thresholding function, some of the cancellous bone was not included; and this created unwanted internal voids in the model. A complete solid model was desired for the custom design phase, and editing of the masks was necessary. Filling of the voids was accomplished by using several editing techniques like cavity fill, draw, and local thresholding.

Mimics uses a smoothing algorithm during the 3D reconstruction phase to create a more realistic model. Unfortunately Mimics does not currently have the ability to export the 3D-model into a CAD format that can be manipulated by standard CAD packages.

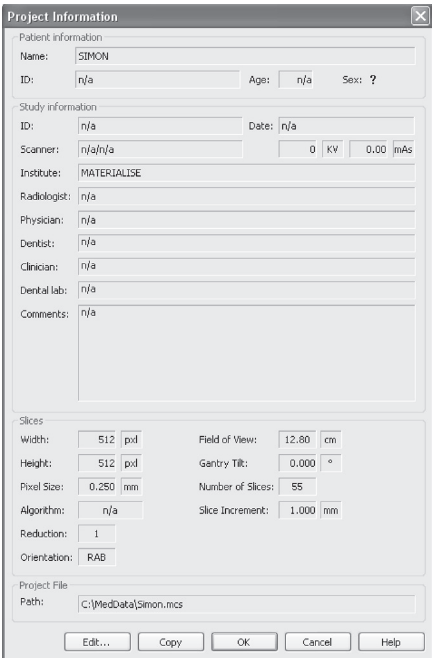
The most efficient method for the required data manipulation was to convert the 3D-model into a STL-file format that could be converted into a 3D CAD format by another software package. The STL-file format is a triangular surface mesh used by the rapid prototyping industry as a standard file format. A STL-file generated by Mimics based on the mask information contains a large number of triangles with various sizes and shapes. For the finite element analysis, the mesh will be based on the STL-file's triangles, which need to be of equal size and shape. The conversion of the STL-file into a CAD-file format can become a cumbersome task because of the uneven triangular mesh. To enhance the STL-file prior to further conversions, the remesh module in Mimics was used. The remesh module is based on a set of algorithms with user-specified parameters that will reshape and resize the triangles through a user-defined number of iterations. After the remesh was completed, the number of triangles had been significantly reduced and the triangular mesh was even in size and shape.

6.1 *CT data processing via Mimics*

In this section data acquired via CT is processed using Mimics. Figure 6 shows a typical CT patient's entry data. The custom design phase is initiated by the acquisition of a Computed Tomography (CT) scan of the patient's mandible. The image data was imported into Mimics version 10.01 for editing and three-dimensional reconstruction. The resolution of the CT images and the slice distance will affect the accuracy of the model. For this project, a CT scan with a XYresolution of 512 × 512 pixels was used, with a resulting pixel size of 0.250 mm and the helical scan was retro reconstructed into 1 mm slices. The total number of slices in the scan was 55, and the scan was performed using 0° gantry tilt. The data processing of CT images are shown in figures from 6 to 9.

6.2 *CBCT data processing via Mimics*

In this section data processing of CBCT using Mimics is shown. Figure 10 shows a typical CBCT patient's entry data. The custom design phase is initiated by the acquisition of the CBCT scan



Project Information

Patient information

Name: SIMON

ID: n/a
Age: n/a
Sex: ?

Study information

ID: n/a
Date: n/a

Scanner: n/a/n/a
0 KV
0.00 mAs

Institute: MATERIALISE

Radiologist: n/a

Physician: n/a

Dentist: n/a

Clinician: n/a

Dental lab: n/a

Comments: n/a

Slices

Width: 512 pxl
Field of View: 12.80 cm

Height: 512 pxl
Gantry Tilt: 0.000 °

Pixel Size: 0.250 mm
Number of Slices: 55

Algorithm: n/a
Slice Increment: 1.000 mm

Reduction: 1

Orientation: RAB

Project File

Path: C:\MedData\Simon.mcs

Figure 6. CT Patient's entry data.

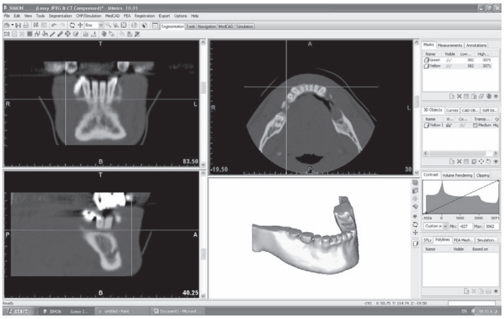


Figure 7. CT data processing.

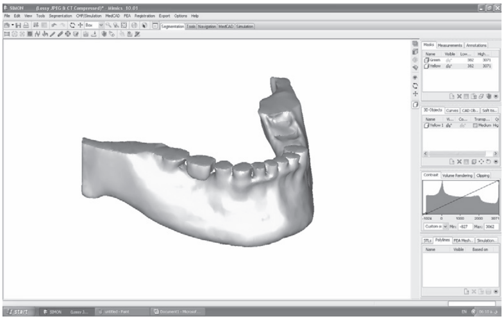


Figure 8. 3D view of mandible.

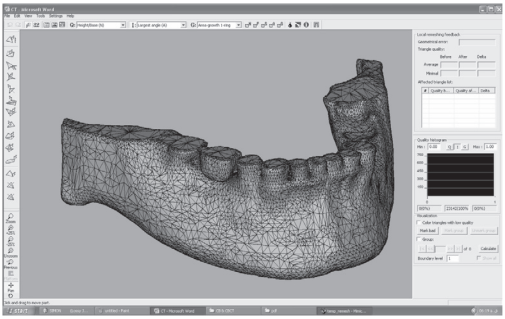
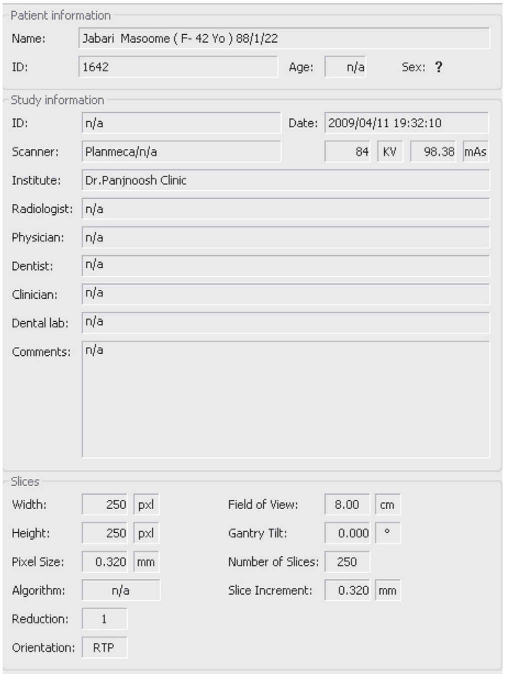


Figure 9. Mandible STL model.



Patient information

Name: Jabari Masoome (F- 42 Yo) 88/1/22

ID: 1642
Age: n/a
Sex: ?

Study information

ID: n/a
Date: 2009/04/11 19:32:10

Scanner: Planmeca/n/a
84 KV
98.38 mAs

Institute: Dr.Panjnoosh Clinic

Radiologist: n/a

Physician: n/a

Dentist: n/a

Clinician: n/a

Dental lab: n/a

Comments: n/a

Slices

Width: 250 pxl
Field of View: 8.00 cm

Height: 250 pxl
Gantry Tilt: 0.000 °

Pixel Size: 0.320 mm
Number of Slices: 250

Algorithm: n/a
Slice Increment: 0.320 mm

Reduction: 1

Orientation: RTP

Figure 10. CBCT Patient's entry data.

of the patient's mandible. The image data was imported into Mimics version 10.01 for editing and three-dimensional reconstruction. The resolution of the CT images and the slice distance will affect the accuracy of the model. For this project, a CBCT scan with a 250 × 250 pixel was used, with a resulting pixel size of 0.320 mm and the helical scan was retro reconstructed into 0.320 mm slices. The total number of slices in the scan was 250, and the scan was performed using 0° gantry tilt. The data processing of CBCT images are shown in figures from 10 to 13.

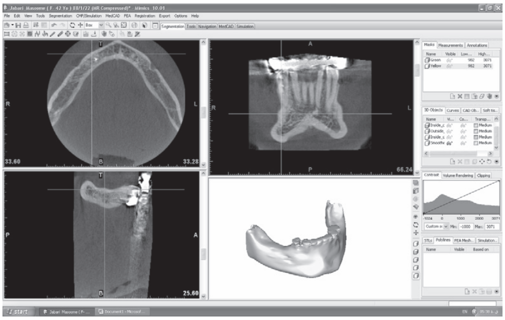


Figure 11. CBCT data processing.

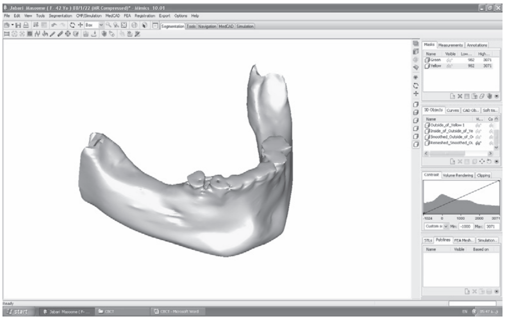


Figure 12. 3D view of mandible.

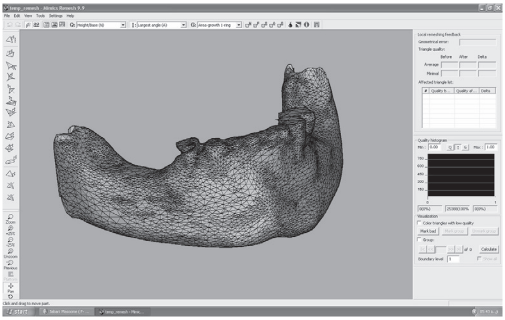


Figure 13. Mandible STL model.

7 DISCUSSION

Considering the results of CT and CBCT data, it can be observed that there is no difference between the results of this two imaging technologies in fabrication of physical models via rapid prototyping technology, because outputs acquired from CT and CBCT data are the same and these outputs can be used for rapid prototyping process. But CBCT has a number of features that makes it suitable for many dental applications over CT such as:

a) *Size and cost*

CBCT equipment has a greatly reduced size and physical footprint compared with conventional CT and it is approximately one fourth to on fifth the cost.

b) *High-Speed Scanning*

Compared with conventional CT, the time for CBCT scanning is substantially reduced and, for most equipment, is less than 30 seconds. This is because the CBCT requires only a single scan to capture the necessary data compared with conventional CT scanners, where several fan beam rotations are required to complete the imaging of an object.

c) *Sub millimeter Resolution*

Currently all CBCT units use megapixel solid-state devices for X-ray detection. These devices provide sub millimeter pixel resolution of component basis projection images. The size of these voxels determines the resolution of image. CBCT produces images with sub millimeter voxel resolution ranging from 0.4 mm to as low as 0.125 mm. Because of this characteristic, coronal and subsequent MPR of CBCT data has the same resolution as axial data. This level of spatial resolution is applicable for maxillofacial applications.

d) *Low Patient Radiation Dose*

The effective dose for various CBCT devices ranges from 52 to 1025 microsieverts (μSv) depending on the type and model of CBCT equipment and imaging protocol used. These values are approximately equivalent to 4 to 77 digital panoramic radiographs (approximately 13.3 μSv) or 5 to 103 days equivalent per capita back ground dose (approximately 3600 μSv in the United States). Patient radiation dose can be lowered by collimating the beam, elevating the chin, and using thyroid and cervical spin shielding. CBCT provides a range of dose reductions of between 51% and 96% compared with conventional head CT (range 1400 to 2100 μSv).

e) *Interactive Analysis*

CBCT data reconstruction and viewing is performed natively by use of a personal computer. In addition, some manufactures provide software with extended functionality for specific applications such as implant placement or orthodontic analysis. Finally, the availability of cursor-driven measurement algorithms provides the practitioner with an interactive capability for real-time dimensional assessment, annotation, and measurements.

8 CONCLUSIONS

CBCT imaging systems have recently been introduced for imaging hard tissue of the maxillofacial region. CBCT is capable of providing accurate, sub millimeter resolution images at shorter scan times, lower dose, and lower costs compared with medical fan-beam CT. Increasing availability of this technology provides the practitioner with an imaging modality capable of providing a 3D representation that is extending maxillofacial imaging from diagnosis to image guidance of operative and surgical procedures.

As mentioned before, one of the major factors affecting the quality of the fabricated dental model, is the data acquisition. In this paper CT and CBCT were compared in fabricating the dental model application. The results demonstrate that CT and CBCT are identical while further advantages of CBCT, makes it more appropriate alternative versus CT during data acquisition. These advantages include:

- Size and Cost
- High speed scanning
- Sub millimeter resolution
- Low patient radiation dose
- Interactive analysis

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