Accuracy assessment of prototypes produced using multi-slice and cone-beam computed tomography

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DOI: 10.1016/j.ijom.2012.04.013

Abstract

The objective of this study was to assess and quantify the dimensional error of prototypes produced using multi-slice and cone-beam computed tomography (MSCT and CBCT). Titanium screws were inserted into a dry skull at different points of the midface. The skull was scanned using MSCT (LightSpeed16®) with pixel size 0.3 mm and CBCT (i-CAT Cone-Beam 3D™) with voxel sizes 0.25 and 0.4 mm. Prototypes were printed (fabricated) using a ZPrinter 310® device. Both the dry skull (gold standard) and the prototypes were measured using a Mitutoyo 3D coordinate measuring system with three perpendicular axes (*X*, *Y*, and *Z*). The prototype produced from MSCT data presented a mean dimensional error of 0.62%; the two models produced with CBCT images yielded errors of 0.74% with voxel size 0.25 mm and 0.82% with voxel size 0.40 mm. No significant differences in dimensional errors were observed across the prototypes ($p = 0.767$; Friedman's non-parametric test). Prototypes produced from CBCT data using voxel sizes of 0.25 and 0.4 mm, and also the one produced from MSCT data using pixel size 0.3 mm, showed acceptable dimensional errors and can therefore be used in the fabrication of prototypes in dentistry.

Key words

cone-beam computerized tomography; helical computed tomography; maxillofacial surgery; facial bones; skeleton

Rapid prototyping (RP) is defined as the production of three-dimensional (3D) physical objects (prototypes) using a virtual model and computer-aided technologies (Computer Aided Design, CAD, and Computer-Aided Manufacturing, CAM). In the field of oral and maxillofacial surgery and traumatology, RP can be used in diagnosis, to simulate osteotomies, resection techniques, and the placement of osseointegrated implants, and also in the planning and treatment of facial defects.[1, 2 and 3]

Volumetric data rendered with CBCT systems have been shown to provide highly accurate data compared with physical measures directly from skulls, with less than 1% relative error.[4] The reliability of 3D surface models obtained with CBCT is similar to that of models obtained with MSCT.[5]

CBCT is associated with lower radiation doses, lower rates of image distortion caused by metal artefacts, and reduced costs compared with MSCT, advantages that have contributed to widespread use of this technique.[4 and 6] Studies are needed to investigate possible errors generated during CBCT image acquisition for RP. No study has reported whether errors in images acquired by CBCT may affect the use of prototypes in dentistry, or whether the dimensional reproducibility of these prototypes is comparable to measures obtained using the gold standard technique (dry skull).

The objective of the present study was to assess and quantify (using percentages) the dimensional error of prototypes of the middle third of a dry skull (gold standard) produced with MSCT and CBCT images.

Materials and methods

The methodology employed in this study consists of sequential procedures aimed at producing and measuring prototypes. It starts with the acquisition of images of a dry skull (gold standard) using MSCT and CBCT and proceeds to the analysis of the resulting replicas (prototypes).

Bone fixation was achieved using 2.0 mm titanium miniscrews (PROMM, Proto Alegre, Brazil), 7 mm long and with head diameters of 3.15 mm. Miniscrews were inserted into a dry skull at different points of the midface, both on the external cortical bone, palatal face, and alveolar ridge. The skull presented (reduced) fractures and lack of co-adaptation at some points, thus allowing a more detailed analysis of the prototypes (Fig. 1).

Fig. 1. Dry skull with titanium screws inserted at different points on the midface.

The skull was placed in a plastic container and immersed in water to simulate the presence of soft tissues without affecting the calibration of the tomography devices.[7 and 8]

MSCT images were obtained using a LightSpeed16 Multi-Slice CT Scanner® (General Electric Medical Systems®, Milwaukee, USA). The following image acquisition protocol was adopted: axial and helical planes, skull filter, 512.512 matrix size, slice spacing of 0.625, pixel size of 0.332, and a resolution of 3.012 pixels per mm.

CBCT images were acquired using an i-CAT Cone-Beam 3D Dental Imaging System (Imaging Sciences International, Hatfield, USA) running the Xoran reconstruction software version 3.1.62 (Xoran Technologies, Ann Arbor, USA). Two CBCT image acquisition protocols were used: 0.25 voxel size, voxel spacing of 0.25, resolution of 4 pixels per mm, and an X-ray tube current of 36 mA; and 0.4 voxel size, voxel spacing of 0.4, resolution of 2.5 pixels per mm, and an X-ray tube current of 18 mA.

Images captured using MSCT and CBCT were saved in DICOM format (digital imaging and communication in medicine) with the following parameters: 120 kVp, 16 bits per pixel, and photometric interpretations via the MonoChrome2 software.

Images were sent to the Technology Laboratory of the Product Development Department at Centro de Pesquisas Renato Archer (CenPRA, Campinas, Brazil) and converted into STL (standard template library) format using the Magics® software (Materialise, Leuven, Belgium). Prototypes were printed (fabricated) using a ZPrinter 310® device (MIT, Burlington, USA).

Following fabrication, both the dry skull and the prototypes were measured using a Mitutoyo 3D coordinate measuring system model B231 (Mitutoyo Sul Americana Ltda., São Paulo, Brazil), with a measurement uncertainty of ± 0.005 mm.

Dimensions were defined geometrically in the 3D space, characterized by three perpendicular coordinate axes: *Z* (vertical axis); *X* (horizontal axis); and *Y* (anteroposterior axis) (Fig. 2). All calculations were based on analytical geometry (i.e. vectors). The origin of the object was point 1, where the three coordinates corresponded to 0.000; all the remaining points were calculated thereafter.

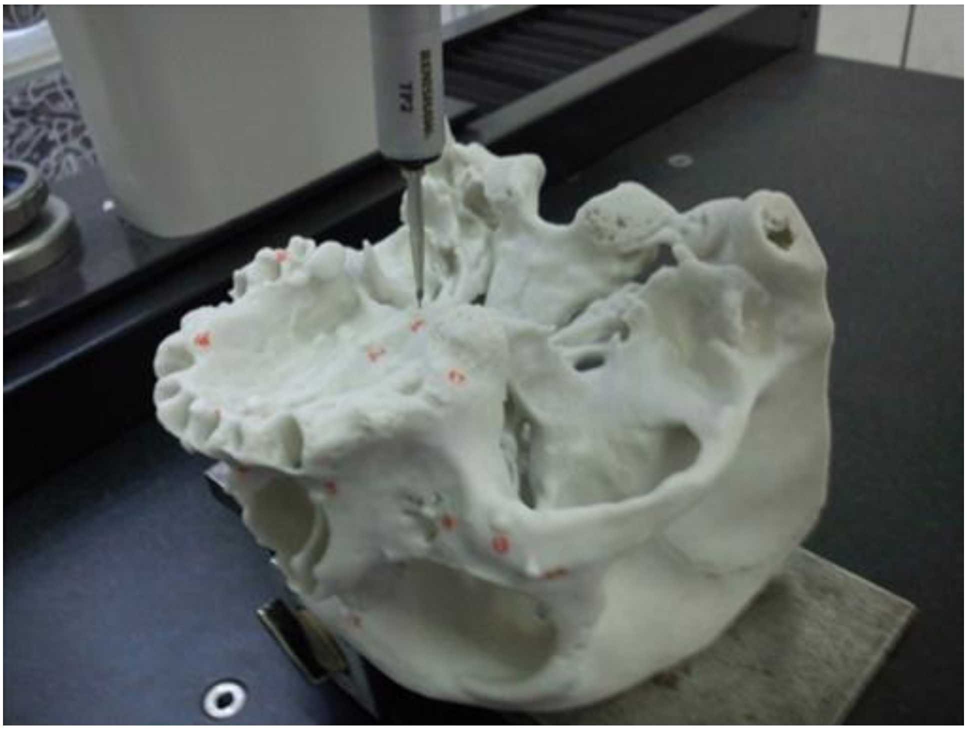

Fig. 2. - Measurement of one of the prototypes.

The dimensional accuracy of the prototypes was determined by comparing coordinates between key landmarks observed on the dry skull and on the prototypes produced with MSCT and CBCT. The relative difference (%) between measurements obtained on the skull and on the prototypes was calculated based on the studies of Choi et al.,[9] Silva et al.,[10] and Ibrahim et al.,[11] considering the mean of 20 repetitions for each measurement, using the formula:

$$\text{Mean relative difference (\%)} = \frac{\text{prototype measurement} - \text{skull measurement} \times 100}{\text{skull measurement}}$$

Results

Mean dimensional errors (%) obtained for the three prototypes in relation to the gold standard (dry skull) on different measurement points and axes are described in Table 1.

Table 1.

Mean dimensional errors (%) observed for the three prototypes in relation to dry skull measurements (gold standard).

	MSCT			CBCT 0.25 voxel size			CBCT 0.4 voxel size		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Point 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Point 2	4.9	3.2	−1.3	2.5	4.6	4.9	3.3	4.3	5.4
Point 3	0.0	1.9	0.3	0.0	1.0	−0.3	0.0	1.9	0.4
Point 4	−1.0	1.7	2.0	−0.3	1.0	−7.0	1.6	0.0	2.6
Point 5	1.0	1.9	1.4	0.5	1.8	−2.1	1.9	0.2	3.8
Point 6	5.9	1.5	0.0	−5.9	3.2	0.0	0.0	0.9	0.0
Point 7	1.5	1.5	−1.2	0.7	1.8	1.8	4.1	1.7	−0.7
Point 8	−1.0	1.5	−3.3	6.9	1.2	2.2	0.2	−0.1	−0.2
Point 9	0.8	2.5	0.1	2.1	0.7	0.3	1.6	0.2	−0.6
Point 10	3.6	2.6	−2.5	6.8	4.2	−1.3	4.4	2.4	−0.5
Point 11	0.6	−2.1	−0.4	0.3	−3.8	2.1	−0.9	−0.6	2.1
Point 12	−0.4	0.8	1.8	0.5	0.6	1.7	0.4	1.0	1.4
Point 13	0.1	−1.5	−1.3	−0.4	1.0	−0.9	−1.1	0.2	−1.3
Point 14	2.5	0.3	1.0	3.2	−0.4	0.0	2.3	−0.5	0.0
Point 15	−2.7	2.4	−1.6	−3.4	0.3	1.1	0.3	−0.7	2.9
Point 16	1.4	2.2	−5.3	3.0	1.8	−6.4	1.5	0.6	−6.6
Point 17	0.7	3.1	3.7	0.4	3.0	4.8	0.9	3.3	0.0
Point 18	1.2	2.6	−5.0	2.1	3.7	−5.3	3.4	1.7	−4.4
Mean	1.1	1.4	−0.6	1.0	1.4	−0.2	1.3	0.9	0.2

MSCT = multi-slice computed tomography; CBCT = cone-beam computed tomography.
Z = vertical axis; *X* = horizontal axis and *Y* = anteroposterior axis.

The prototype obtained with MSCT images presented a mean dimensional error of 0.62%, compared to 0.74% on the prototype produced with CBCT and a 0.25 mm voxel size, and 0.82% with CBCT and a 0.40 mm voxel size. No significant differences were observed between the groups in terms of percentage variations ($p = 0.767$; Friedman's non-parametric test).

Discussion

Every step in the RP process is prone to error, regardless of the specific techniques employed in each case. Errors may occur during the acquisition of CT data, during image manipulation, or during model fabrication and finishing. CT image acquisition, for example, can be influenced by the system available, or by the acquisition technique or scanning protocol adopted. Such dimensional errors should be kept to a minimum so that the final quality of prototypes or their clinical application is not affected.[12]

The device used to obtain CT images plays a major role, once image quality is intimately related with 3D surface model accuracy. Errors produced at this stage can be related to different parameters, such as slice thickness (main factor[13]), movement of the operating table, gantry inclination, voltage, patient movement, presence of intraoral metal artefacts, and image reconstruction slice thickness on the algorithm. In particular, 3D surface model accuracy is directly determined by the slice thickness specified on the CT scanner during image acquisition. Thinner slice thicknesses naturally yield more accurate models, but also mean longer exposure to radiation, which explains the dilemma involved in determining optimal slice thickness.[9]

The parameters set for the acquisition of CT and CBCT data are related to the coordinate system: width is related to axis *X* and height to axis *Y*. Each 2D square formed by *X* and *Y* is called a pixel (picture element). The resulting image is made up of such pixels, which vary in number depending on the acquisition matrix size defined for each slice. If the *Z* axis is also taken into consideration, the result will be a cube, or a voxel (volume element). Smaller voxel sizes produce higher resolution images, but they expose the patient to higher doses of radiation. [14] Although previous studies have shown high accuracy levels for CBCT-derived linear measurements, [15 and 16] the influence of voxel size on the accuracy of prototypes has not been investigated. Ballrick et al. [17] have suggested that a voxel size of 0.4 mm is adequate to measure craniofacial structures on surface models. In the present study, no significant differences were observed between the two image acquisition methods assessed (MSCT and CBCT) or between the two voxel sizes used on CBCT (0.25 and 0.4 mm) in the assessment of dimensional errors associated with the prototypes.

The fabrication of prototypes of the midface is subject to a lower degree of precision in the modelling and preservation of thin surfaces and small projections commonly found in this region. For example, loss of detail has been reported in the anterior wall of the maxillary sinus and in the orbital floor.[18] Measurement errors are inevitable, and may be caused by the operator (human error), or by instrument accuracy.[9]

The selection of craniometric landmarks (most common human error[9]) and the generation of coordinate points on the prototypes are more prone to error. Although, in the present study, instruments were handled by an experienced professional, accuracy and resolution errors are inherent in the technique. The usual technical difficulty related to locating the landmarks on the prototypes was not observed in this study, once the titanium screws inserted into the dry skull appeared clearly on the printed prototypes. The heads of the titanium screws, which can be used as a marker to evaluate prototype accuracy, had a diameter of 3.15 mm, so were larger than the voxel sizes used in the CBCT (0.25 and 0.4 mm) and MSCT (0.3 mm) image acquisition protocols. In order to minimize craniometric errors, each landmark was measured 20 times. The results revealed similar dimensional errors in axes *X*, *Y*, and *Z*, regardless of the protocol adopted, so all three prototyping protocols produced similar errors in different planes. In the assessment of prototypes, the relative analysis of distortion also takes into account the magnitude of the real value (skull). Therefore, values around point 1 suggest the presence of high levels of distortion in spite of a low number of errors found.

The dimensional errors obtained in this study with CBCT (0.74% with voxel size 0.25 mm and 0.82% with voxel size 0.40 mm) and MSCT (0.62%) were within acceptable values. Asaumi et al.[19]

have suggested that dimensional errors below 2% do not interfere with the surgical applicability of prototypes. It is still necessary to identify the required level of accuracy for prototyping methods in oral and maxillofacial surgical procedures and to adapt such prototypes to each procedure. The dimensional accuracy results found in this study are accurate enough to allow the use of the prototypes during communication with the patient, diagnosis, and presurgical planning, especially in more complex cases, such as traumatic injuries, tumour resection, and severe facial defects, as recommended by Winder and Bibb.[12]

The dimensional errors observed in the present prototypes in relation to the dry skull (gold standard) are compatible with those reported by Asaumi et al.[19] and Choi et al.[9] who found errors ranging from 0.56 to 0.64% with Fan Beam Computed Tomography (FBCT). The present findings were lower and therefore more accurate than those reported by Chang et al.,[18] Silva et al.,[10] and Ibrahim et al.,[11] who obtained distortion values of 1.79–4.7%.

Prototyping parameters for use with FBCT have been defined previously.[9, 10, 11, 18 and 19] The aim of the present study was to identify criteria that support the feasibility of using CBCT to obtain images for use in RP, once this method is commonly and specifically used by dental surgeons. The findings were similar to those reported in the literature and show that prototypes produced from CBCT data can be used in dental practice. The dimensional errors observed were below 2%, not affecting prototype applicability, according to the suggestion by Asaumi et al.[19] The methodology included a prototype fabricated with MSCT data, to allow comparison between two image acquisition methods used in the same RP process, with no significant differences observed in terms of dimensional errors. Further studies are warranted to confirm the dimensional errors reported here and to assess prototypes produced from CBCT data qualitatively, with a special focus on thin and delicate structures, such as orbital walls, in which a higher voxel resolution may be necessary.

The facial prototype of a patient presenting with traumatic injuries allows precise reproduction of the defects to be treated and can reveal details of the regional anatomy and bone structure and of the interface between bone and adjacent tissues. Li et al.[20] have reported on the effectiveness of RP in the diagnosis, planning and preoperative simulation of a surgical procedure to repair fractures of the zygomatic-orbital-maxillary complex. The authors were able to locate the osteotomy precisely during surgery, to reposition the bone fragment adequately, and to predict surgical outcomes.

A study conducted by Zhang et al.[21] has shown that RP allows more precise and more symmetric surgical reconstruction of the temporomandibular joint, to improve mandibular function, and to increase the effectiveness of reconstruction. Owing to the close anatomic relationship between the temporomandibular joint and other important anatomic structures, dimensional errors obtained on prototypes should be taken into consideration when dimensions are transferred to the patient. This procedure is essential to avoid intraoperative accidents, such as rupture of the maxillary artery.

In this study, a higher voxel resolution did not have significant effects on the measurement of prototypes produced from CBCT data. This finding, combined with the advantages of a lower voxel resolution, such as shorter scanning time, lower exposure to radiation, and less patient movement, suggests that preference should be given to lower resolutions. Conversely, measurements obtained with lower voxel sizes should be interpreted with care, as the diagnostic capacity of CBCT images seems to be influenced by this parameter. Liedke et al.,[22] for example, have shown that voxel sizes of 0.3 and 0.2 mm yielded better results when compared with voxel size 0.4 mm to diagnose external root resorption, which suggests that an image acquisition protocol with voxel size 0.40 mm may not be adequate for all patients and indications. Voxel resolutions should be defined individually for each case, depending on the indication and characteristics of each patient and treatment plan.

The use of CBCT images for the 3D reconstruction of oral and maxillofacial models using 0.25 and 0.40 mm voxel sizes, and of MSCT using a pixel size of 0.3 mm, are acceptable imaging methods for the fabrication of prototypes in dentistry.

Funding

None.

Competing interests

None declared.

Ethical approval

The research protocol of the present study was approved by the Research Ethics Committee at Universidade Luterana do Brasil (ULBRA), Canoas (protocol no. 2010-462H).

Acknowledgements

The authors are grateful to the Division of 3D Technologies at Centro de Pesquisas Renato Archer (CenPRA) and to Clínica de Radiologia Odontológica Dior Center, located in Porto Alegre, Brazil.

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