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The impact of different cone beam computed tomography and multi-slice computed tomography scan parameters on virtual three-dimensional model accuracy using a highly precise *ex vivo* evaluation method

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Objectives: Multi-slice computed tomography (MSCT) and cone beam computed tomography (CBCT) are indispensable imaging techniques in advanced medicine. The possibility of creating virtual and corporal three-dimensional (3D) models enables detailed planning in craniofacial and oral surgery. The objective of this study was to evaluate the impact of different scan protocols for CBCT and MSCT on virtual 3D model accuracy using a software-based evaluation method that excludes human measurement errors.
Material and methods: MSCT and CBCT scans with different manufacturers' predefined scan protocols were obtained from a human lower jaw and were superimposed with a master model generated by an optical scan of an industrial noncontact scanner. To determine the accuracy, the mean and standard deviations were calculated, and t-tests were used for comparisons between the different settings.
Results: Averaged over 10 repeated X-ray scans per method and 19 measurement points per scan ($n = 190$), it was found that the MSCT scan protocol 140 kV delivered the most accurate virtual 3D model, with a mean deviation of 0.106 mm compared to the master model. Only the CBCT scans with 0.2-voxel resolution delivered a similar accurate 3D model (mean deviation 0.119 mm).
Conclusion: Within the limitations of this study, it was demonstrated that the accuracy of a 3D model of the lower jaw depends on the protocol used for MSCT and CBCT scans.

1. Introduction

Multi-slice computed tomography (MSCT) is an indispensable imaging technique in advanced medical diagnostics. Moreover, the tomographic images can serve as a basis for digital geometry processing. At this, the 2-dimensional virtual slices are assembled to generate a virtual three-dimensional (3D) model, which can be applied to plan and simulate surgical procedures in detail (Nkenke et al., 2004; Xia et al., 2000a, 2000b). In addition, corporal models can be fabricated using a 3D printer; this method is already an integral part for a state-of-the-art treatment in advanced craniofacial surgery and might gain in importance in dental implantology (Motohashi and Kuroda, 1999; Olszewski et al., 2014; Olszewski, 2013; Jardini et al., 2014), as radiological images and the corresponding virtual 3D models can be matched with scanned plaster models or intraoral scans and optical images (Noh et al., 2011; Plooij

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et al., 2011; Nickenig and Eitner, 2010; Nickenig et al., 2010). Through this, implant positions or orthognatic operations can be predetermined and the outcomes can be evaluated (Chen and Chen, 1999; Eggers et al., 2006, 2009). In the oral and maxillofacial area, cone beam computed tomography (CBCT) has emerged as a serious alternative to the MSCT in recent years, as CBCT can be performed in a dental practice (Eggers et al., 2009; Carrafiello et al., 2010; Ludlow and Ivanovic, 2008). In this context, the main indications for this X-ray imaging procedure are the exact determination of the location of impacted teeth and the accurate planning of dental implants (Hol et al., 2015). It was demonstrated that the accuracy of the virtual 3D model is a fundamental prerequisite for a successful implant insertion by a fully guided surgical template (Nickenig et al., 2012; Weitz et al., 2011). As the radiological image provides the basis for the 3D model, two questions arise: Which imaging method delivers the most accurate data set? To what extent is the 3D model accuracy affected by radiographic parameters? Based on answers to these questions, we can make a point about which parameters should be chosen in order to develop a sufficient 3D model. This issue has already been investigated by the determination of linear deviations and might be biased by human measurement errors (Al-Ekrish and Ekram, 2011; Gaia et al., 2013; Ganguly et al., 2011; Whyms et al., 2013; Veyre-Goulet et al., 2008). Thus, a highly precise 3D measurement method that excludes human measurement errors was chosen for this study (von Wilmowsky et al., 2015).

2. Material and methods

2.1. Master model

The Institute of Anatomy (Department I, Friedrich-Alexander-University of Erlangen-Nuremberg) furnished a macerated lower jaw that was used as a master model in this study. The mandible was assembled with self-sticking reference markers (GOM mbh, Braunschweig, Germany), and the surface was sprayed with a rutile (TiO_2) and ethanol (95%) mixture (Rutile Titanium White; GOM mbh, Braunschweig, Germany). In order to protect the reference markers from pollution, they were covered with silicon during the rutile application. Subsequently, the jaw was measured optically with a white light scanner (ATOS SO II, GOM mbh Braunschweig, Germany) (Fig. 1). Within the applied measuring volume of $90 \times 72 \times 50$ mm, a probing error of 0.004 mm is specified by the manufacturer. The accruing virtual master model was oriented in the 3D space via the reference markers, and the data were saved in STL file format.

2.2. CBCT and MSCT scans

To investigate the impact of different scan parameters on the 3D model accuracy, the mandible was examined with an MSCT scanner (SOMATOM Definition AS, Siemens, Erlangen, Germany) at the Institute of Radiology (Friedrich-Alexander-University of Erlangen-Nuremberg) using a slice thickness of 0.75 mm, a pitch factor of 0.9, and different tube voltages (80, 100, and 140 kV); for each setting, the scan was repeated 10 times. For 3D rendering, data were reconstructed using a hard tissue kernel H70. The images were reconstructed with 0.75-mm section thickness, 0.5-mm section interval, and field of view (FOV) of 155 mm. The CBCT system 3D eXam (KaVo dental GmbH, Biberach, Germany) served to obtain different CBCT images from the mandible. Three different clinical scan protocols were used in this study. A high-resolution protocol with 0.2-mm voxel size, 5 mA at 120 kV, a FOV_{xy} of 160 mm and FOV_z of 75 mm, and an exposure times of 14.7 s; and two standard protocols with a voxel size of 0.3 mm, 0.4 mm, and 5 mA at 120 kV, a FOV_{xy} of 160 mm and FOV_z of 75 mm, and an exposure time of 8.9 s. The scans were performed 10 times for each setting, as well.

2.3. Data processing and measurements

Every examination was stored as a DICOM data file with the assistance of the export function of the original software of the respective scanner. Each of the 60 DICOM data sets was transferred to an STL file using appropriate software (ImpactView 4.4, CT Imaging GmbH, Erlangen, Germany). Subsequently, the STL files were imported into a computer-aided design (CAD) interactive software (GOM Inspect; GOM mbH, Braunschweig, Germany) for data analysis. von Wilmowsky et al. (2015) established a method to evaluate the 3D accuracy of digital image data. According to this method, the master model STL file (scanned by ATOS II) was selected as reference value (ref) and compared to each STL file from the MSCT/CBCT scans, which was set as the actual value (act). Therefore, preregistration of the three dimensions was performed with the aid of three anatomical landmarks that were selected manually, resulting in the 3D models being overlaid roughly. According to a uniquely defined best-fit area, the models were superimposed automatically by the software. Based on 19 measurement spots (which were located on the vestibular and lingual curvature of the mandibular arch), the aggregate discrepancy between both models was calculated as Euclidean distance (in xyz-axis):

$$\mathrm{d}xyz = \sqrt{\left(x_{ref} - x_{act}\right)^2 + \left(y_{ref} - y_{act}\right)^2 + \left(z_{ref} - z_{act}\right)^2}$$

Furthermore, a false color image was generated (Figs. 2 and 3).

2.4. Statistical analysis

All statistical analysis was done using the statistical programming language R version 3.1.1 (Development Core Team R, 2013). To perform statistical tests without obtaining false significant results because of repeated measurements, we averaged all measurements for each of the 19 spots. Statistical tests were performed using 19 values per method. We performed an analysis of variance and then did all pairwise comparisons with the t test. To correct for multiple testing, we used the Benjamini–Hochberg method (Benjamini and Hochberg, 1995). A corrected p value of less than 0.05 was considered significant.

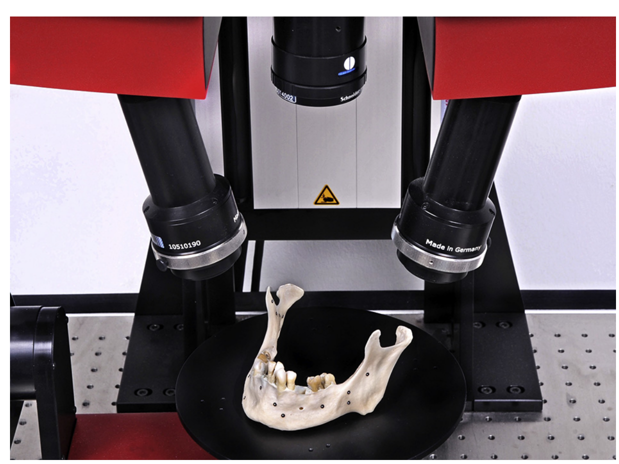

Fig. 1. Industrial white light scanner ATOS II with the human mandible glued with reference points.