Head positioning in a cone beam computed tomography unit and the effect on accuracy of the three-dimensional surface mode

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Head position during cone beam computed tomography (CBCT) examination can easily deviate from the ideal, which may affect the accuracy of the segmented three-dimensional (3D) model. The aim of this study was to determine the effect of head positioning on the accuracy of the 3D model. A human dry skull was positioned at predetermined orientations in a CBCT scanner and scanned in multiple orientations and voxel sizes. The resulting 3D surface models were superimposed over those derived from the reproducible centered positioned skull with 0° inclination. Color mapping and analysis of the differences expressed by the root mean square error (RMSE) were performed. The RMSE for each orientation using the 0.3 mm voxel ranged from 0.31 to 0.87 mm for the whole maxillofacial region, from 0.44 to 0.91 mm in the maxilla, and from 0.31 to 0.72 mm in the mandible. For the 0.4 mm voxel, the RMSE ranged from 0.47 to 0.86 mm for the whole maxillofacial region, from 0.60 to 0.96 mm in the maxilla, and from 0.56 to 0.86 mm in the mandible. The maxilla showed a slightly higher deviation than the mandible in both voxel groups. It can be concluded that the head position affects the accuracy of the segmented 3D model, but the inaccuracy does not exceed clinically relevant levels.

Factors known to influence the accuracy of a segmentation are scanner-related [scanner performance, field of view size, artifact tolerance, voxel size, and other hardware-related parameters (13–16)], operator-related [the software employed and the operator performing the segmentation (17–19)], and patient-related [the tissue properties, induction of scatter radiation, metal artifacts from prosthetics, and patient movement (20–22)]. Amongst patient-related factors, head orientation has been considered as a potential influencing factor for CBCT systems, as opposed to medical CT scanners, as the former features a cone-shaped beam that rotates once around the patient head, in contrast to the fan-shaped beam with continuous helical movement of the latter. The accuracy of measurements on CBCT images has been reported in the literature, including a few studies on the positioning effect, but with controversial results (23–26). These studies are either based on two-dimensional (2D) reconstructed images or mainly performing linear and angular measurements on specifically selected landmarks, or are limited to a single axis deviation in positioning of the objects examined.
A positioning envelope, out of which errors in the 3D surface-rendered hard tissue models may be induced, has not previously been determined. It requires multiple, well-controlled positioning changes for the test model and global detection of surface differences compared with the optimally positioned reference model. Linear and angular measurements of specific landmarks and estimation of signed averages may not be sufficient to thoroughly detect the inaccuracies of a tested 3D model in its whole. Precise registration of the surface inaccuracies between two rendered models requires analysis of the differences for their whole surfaces, as expressed by the root mean square error (RMSE) (27, 28), which has been overlooked in previous studies.

The aim of this research was to investigate the effect of head positioning on the accuracy of the segmented 3D surface model using 3D superimposition for detection of surface differences and to determine the positioning envelope for error-free 3D hard tissue segmentation, relative to a predetermined, reproducible centered position (RCP).

Material and methods

The dry skull of an anonymous adult man with complete dentition was positioned at predetermined orientations in a KaVo 3D cone beam CT unit (KaVo Dental, Bismarckring, Germany; Fig. 1) with a minimum voxel size of 0.3 mm for the 170 x 230 mm field of view. The skull was scanned using two voxel sizes at 0.3 and 0.4 mm, using fixed exposure and a field of view of 17 mm. A specially manufactured 3D positioning platform (29) was used for precise orientation of the skull (Fig. 2). In total, 24 different offset orientations were tested in the range of −20° to +20° pitch and −15° to +15° roll, related to a reproducible position. For practical reasons, an RCP in relation to the Frankfurt horizontal plane was used in the present study. The RCP was aligned, aided by the reference laser lines provided by the CBCT unit in its standard setting, in the center of the field of view. The pitch steps were standardized to be −20°, −10°, 0°, +10° or +20°. For the roll, steps of 7.5° were used, resulting in orientations of −15°, −7.5°, 0°, +7.5° and +15° compared with the RCP. The offsets were arbitrarily chosen within a range of clinical relevance regarding pitch and roll. Positioning of the skull in the field of view according to the above-mentioned inclinations was aided by the laser positioning reference lines of the unit. Two scans were performed at every position, one for each voxel size setting. The DICOM data provided by each scan were then exported from the unit’s dedicated software and imported to specialized software (DEVIDE v12.2.7; TU Delft, Delft, the Netherlands) for segmentation (30). This was a semi-automated hard tissue segmentation process based on double thresholding using pixel intensity differentiation and 3D region growing in combination with active contour tracing; a minimum of −750 density units and a maximum of 3,071 density units were used for the segmentation. The segmented hard tissue data were finally transformed to a polygon 3D model, with approximately five to six million surface polygons. After trimming and using the marching cubes algorithm provided by the software (31), approximately one million surface polygons per skull remained after decimation (Fig. 3).

The 3D models for each orientation (test models) were subsequently imported in Geomagic Studio version 2012 (Geomagic Solutions, Los Angeles, CA, USA) for volumetric comparison with the model derived from the centered, non-rotated position (reference model). First of all, the maxillofacial region of interest was defined on all models as the volume underneath the Frankfurt horizontal plane.
plane passing through the orbita (Orb) and the porion (Po) points and ventrally to the perpendicular vertical plane at the Po points (Fig. 4). Then, the registration procedure was performed based on initial manual registration (Fig. 5) followed by automatic best-fit matching using the iterative closest point algorithm for optimal superimposition of the test models over the reference model (Fig. 6). At this point, analysis of the model differences was carried out and the surface discrepancies were visualized by color mapping (Fig. 7). Additionally, quantitative comparisons of the two models were performed based on the RMSE of the differences $X_{\text{test},i} - X_{\text{reference},i}$ between the two surfaces.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{\text{test},i} - X_{\text{reference},i})^2}{n}}$$

The software provides the mean positive and negative differences for all individual surface points where the test model lies within or outside the reference model, followed by the RMSE which represents the magnitude of inaccuracy of the tested model. For each tested model, RMSE values were calculated for three regions of interest: the whole maxillofacial region, as well as separately for the maxilla and for the mandible.

**Statistical analysis**

Descriptive statistics, including the overall mean difference, signed averages for positive and negative differences, SD of the signed averages, and RMSE estimates, were calculated for each rendered model using the Geomagic Studio version 2012 software. For statistical analysis of the results, we used the software package IBM spss Statistics.
for Windows, Version 22.0 (Armonk, NY, USA). Specifically, to determine the test–retest variability of the method, we used the coefficient of repeatability (CR) as an absolute reliability index. The scans and the measurements for the RCP were repeated three times with a 1-wk intervening interval between measurements, and the absolute variability was determined using the coefficient of repeatability (CR). The CR is calculated as follows: 

$$CR = 1.96 \times \frac{s}{\sqrt{n}}$$

where $s$ is the standard deviation of the differences between the measurements, and $n$ is the number of measurements.

The CR values for the method were calculated, and the results indicated that the method has a high level of reliability, with CR values of less than 0.05.

For the segmentation analysis, the three-dimensional (3D) color mapping of the segmentation differences was performed. In this example, the reference model (scanned optimally, centered, and leveled with the Frankfurt plane parallel to the ground) was superimposed and compared with a test model that was scanned with a 20° pitch and 15° roll inclination, at a voxel size setting of 0.3 mm. The differences between the models are color-mapped using the scale on the right (units in mm). The calculated root mean square error (RMSE) in this case was 0.625 mm.

Fig. 5. Initial superimposition of models derived from scans with different orientations. After obtaining the models scanned with different orientations (grey, centered; blue, offset) and by directly superimposing them, the difference in the positioning of the skull is apparent: pitch difference (A), roll difference (B), and combination of both (C).

Fig. 6. The superimposed three-dimensional (3D) models after registration and best-fit matching. The 3D models of the hard tissues are registered and optimally matched using the best-fit method based on detecting the least square differences. Optimally matched models from an oblique view (A) and from a top view (B) are shown. The yellow color denotes the internal surfaces of the polygons.

Fig. 7. Three-dimensional (3D) color mapping of the segmentation differences. In this example, the reference model (scanned optimally, centered, and leveled with the Frankfurt plane parallel to the ground) is superimposed and compared with a test model that was scanned with a 20° pitch and 15° roll inclination, at a voxel size setting of 0.3 mm. The differences between the models are color-mapped using the scale on the right (units in mm). The calculated root mean square error (RMSE) in this case was 0.625 mm.
differences were recorded. The values below which these absolute differences between two measurements would lie with 0.95 probability (95% CI) were then calculated and expressed as the CR (32). The mean RMSE values, together with the CR, reflect the maximum accuracy that can optimally be obtained for the given voxel size and were used as the reference values against which the RMSE of different angulations was tested for differences.

Results

The repeated measurements for the RCP revealed a CR of 0.05 mm with a mean RMSE of 0.31 mm for the 0.3 mm voxel size (i.e. measurements differing within 0.31 ± 0.05 mm could be considered as interchangeable), whereas the corresponding numbers for the 0.4 mm voxel size (reference values) were a mean RMSE of 0.47 mm (i.e. measurements differing within 0.47 ± 0.05 mm could be considered as interchangeable).

The RMSE for different angulations in pitch and roll using the 0.3 mm voxel size ranged from 0.31 to 0.87 mm for the whole maxillofacial region, generally increasing with increasing angulation. Table 1 presents the RMSE values for the overall measurements with the 0.3 mm voxel size. The RMSE values varied from 0.34 to 0.91 mm for the maxilla and from 0.31 to 0.72 mm for the mandible (Fig. 8). For the 0.4 mm voxel size, the RMSE for the whole maxillofacial region was between 0.47 and 0.90 mm, while the corresponding values for the maxilla ranged from 0.49 to 0.96 mm and those for the mandible from 0.47 to 0.82 mm (Fig. 9). Paired t-test revealed significant differences \( P < 0.001 \) for all regions of interest between the RMSE values of the different orientations and the reference value of 0.31 mm for the 0.3 mm voxel size. Significant differences \( P < 0.001 \) for all regions of interest were also found between the RMSE values of all different orientations and the reference value of 0.47 mm for the 0.4 mm voxel size. Differences between the two voxel size groups were significant according to the paired t-test \( P < 0.005 \) for the maxillofacial area and \( P < 0.001 \) for either the maxilla or the mandible separately.

The error-free positioning envelope relative to the RCP, based on a clinical significance level of 0.5 mm accuracy, was found to extend slightly beyond inclinations of 7.5° pitch and 10° roll for the whole maxillofacial region or the maxilla alone at 0.3 mm voxel size and reaching up to 15° and 10°, respectively, when only the mandible was tested (Fig. 8). For the 0.4 mm voxel size, the envelope was confined under 7.5° pitching and 10° rolling of the skull for all regions (Fig. 9).

Discussion

Reduced-dose CBCT for 3D imaging of the craniofacial structures is increasingly used in oral and maxillofacial disciplines as a result of the wide array of applications offered, ranging from 3D diagnostic cephalometrics and overtreatment simulation of severe facial anomalies to virtual planning of complicated orthognathic deformities. However, several factors may affect the accuracy of the image. One is the position of the skull in the field of view. However, we tried to minimize this parameter by positioning the dry skull in the center of the field of view aided by the laser positioning reference lines. Other factors that could affect the accuracy are the orientation, objects outside the field of view, and the voxel size (33, 34). One of the main shortcomings of the present study is that we used a dry human skull. Soft tissues do influence the voxel intensity in the CBCT scan, thereby influencing the accuracy of the rendered hard tissue. Because the skull was placed on a 3D positioning platform, there is an object outside the field of view which also influences the accuracy (35, 36).

The common denominator in the above-mentioned applications is the rendered 3D surface models of the hard tissues derived from the CBCT data by the so-called segmentation process. This process comprises several steps essentially introducing a series of parameters that may influence the accuracy of the segmented outcome. It is therefore imperative to control all other parameters in order to focus only on the effect of the specific variable of interest on the accuracy of the segmented 3D surface model. The segmentation part of the present study was operator-independent. This was achieved by using a semi-automated, script-based segmentation process with set threshold values for the specific skull. Other factors, such as CBCT unit and technique, and operator-dependent factors, may still influence the outcome. The voxel size setting is another parameter that may affect the accuracy of a surface-rendered 3D model as a result of the partial volume effect. Concerning these settings, the study by Maret et al. (15) indicated that the accuracy of the models appears to be connected to the voxel size, although the differences between the models were small and not always clinically relevant. Damstra et al. (37) did not find increased accuracy of linear measurements on segmented surface models when decreasing the voxel size from 0.4 to 0.25 mm. Our study, using voxel sizes of 0.3 and 0.4 mm, showed that there is a significantly

Table 1

<table>
<thead>
<tr>
<th>Roll (°)</th>
<th>X</th>
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<tbody>
<tr>
<td></td>
<td>20°</td>
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<tr>
<td>Pitch (°)</td>
<td></td>
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<tr>
<td>15°</td>
<td>0.692</td>
</tr>
<tr>
<td>7.5°</td>
<td>0.665</td>
</tr>
<tr>
<td>0°</td>
<td>0.715</td>
</tr>
<tr>
<td>-7.5°</td>
<td>0.678</td>
</tr>
<tr>
<td>-15°</td>
<td>0.729</td>
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Values are given in mm and represent different combinations of roll and pitch.
increased accuracy with the smaller voxel size. Interestingly, the mean difference between the two voxel sizes for all orientations was found to be 0.10 mm, reflecting perfectly the absolute difference in voxel size, a finding that is nevertheless far from being qualified as clinically significant.

Only a few studies could be found in the literature on the effect of positioning on the accuracy of the measurements in images obtained from CBCT. These studies were mainly based on linear measurements on the reconstructed models and showed variable results regarding the effect of the positioning (23–26). However, the present study compared, for the first time for this purpose, the 3D surface of the examined region of the skull, decimated down to a million points, which allowed us to reveal differences of up to almost 1 mm in the 3D model accuracy between different head orientations. These differences were not only statistically significant but also clinically meaningful, as 0.5 mm is generally regarded as the acceptable accuracy threshold. Although this threshold is debatable, in particular cases where the differences are less clinically important the ‘error-free envelope’ tends to be bigger in that case. In this study, we made a proposal of an ‘error-free envelope’ relative to the RCP with a clinical deviation of 0.5 mm.

In pursuit of determining a positioning envelope for error-free hard-tissue segmentation, the need arises to quantify, in greater detail, the differences between the tested models deriving from different orientations. A characteristic measure of the inaccuracy of a model when compared with a reference is the RMSE. For the higher resolution of 0.3 mm voxel size, the RMSE ranged from 0.31 to 0.87 mm. Overall, lower error values were recorded for the mandible than for the maxilla. The latter contributes mainly to the relative inaccuracy.

**Fig. 8.** Color graph of the root mean square error (RMSE) values for each head inclination, with data shown in degrees (voxel size 0.3 mm), for the whole maxillofacial region and for the maxilla and mandible separately. (A) Two-dimensional (2D) color-mapped graph. The color mapping scale extends from green to yellow and orange to red with increasing levels of inaccuracy. The green areas denote the error-free envelope relative to the reproducible centered position (RCP), where RMSE values are smaller than the clinically significant level of 0.5 mm. (B) Three-dimensional (3D) color-mapped graph. Inclinations of the head resulting in errors from 0.3 to 0.5 mm are marked green, from 0.5 to 0.7 mm yellow, and from 0.7 to 0.9 mm and beyond are marked red. The height of the peaks denotes the level of inaccuracy. Inclinations of the head resulting in RMSE values smaller than the clinically significant level of 0.5 mm are considered to fall within the error-free positioning envelope relative to the RCP (green valleys). More data were included in this figure than shown; these data were interpolated for visualization purposes.
of the entire maxillofacial complex as a result of its thinner cortical plates. The same pattern was found for the lower resolution of 0.4 mm voxel size, although all RMSE values were higher, ranging from 0.47 to 0.90 mm, reflecting the somewhat less-accurate 3D model on this lowered resolution. The highest inaccuracy value recorded for both voxel sizes was close to, but did not exceed, 1 mm at the very extreme ends of positioning deviation.

The second step in determining the error-free positioning envelope relative to the RCP is the determination of an error level beyond which a model would be considered inaccurate for clinical purposes. Such a significance level is usually set according to the demands of the clinical application of the method. One such example is orthognathic surgery. Virtual planning for patients requiring orthognathic surgery is highly dependent on the accuracy of both the 3D skeletal surface model and the depiction of the covering facial soft tissues for valid simulation. A value set as clinically significant in these applications is usually 0.5 mm (38). Stereophotography is another modern application that makes use of the CBCT data by fusing the segmented bone models onto the 3D photographic captures of the soft tissues, making it possible to assess their interrelationship. An accurately rendered surface of the underlying bone segment would lead to reliable estimation of soft tissue thicknesses in facial regions. This technique,
initially applied in forensic sciences, has lately gained much interest in computer-assisted craniofacial surgery for patients with soft tissue and underlying hard tissue defects. It comprises preoperative virtual planning, reconstruction of the defects, and prosthetic rehabilitation by 3D-printed implants. In such applications, a highly accurate 3D hard tissue model is particularly desirable, although in real practice transferring virtual models and operation maneuvers in the operation room remains a challenge, resulting in accuracy margins larger than 0.5 mm (and often up to 1.0 mm) (39, 40).

Computer-assisted surgery navigation is another advanced application, in which the 3D-rendered hard tissue models play a significant role. Several systems have been developed based on either surface laser scanning or navigational markers and beacons, in which the hard tissue model is used for guiding the surgeon, for example, through the fractured orbital floor during blow-out surgical management of a blow-out fracture. Although the levels of technical accuracy in some reports go below 0.5 mm, the actual precision realized in the clinical practice still falls between 0.5 and 1.0 mm (41, 42).

We determined the error-free positioning envelope, relative to the RCP, by setting the RMSE of 0.5 mm as the threshold level for clinical relevance. The RMSE values of >0.5 mm are flagged as clinically significant inaccuracies, and the respective tested models are deemed inaccurate, while operating within the positioning envelope results in models that can be considered as no different from the RCP. In the present study, the error-free positioning envelope was found to extend beyond inclinations of 7.5° pitching and 10° rolling for the whole maxillofacial region at 0.3 mm voxel size and reached up to 15° and 10°, respectively, when only the mandible was tested. For the 0.4 mm voxel size, the envelope is confined by 7.5° pitching and 10° rolling of the skull for all regions, reflecting the lower tolerance of the larger voxel size for positioning deviations.

Regarding the external validity of the above findings, it is essential to stress the fact that the absolute values of the error-free positioning envelope might be CBCT unit specific. Image quality properties of different CBCT units, such as geometric correction algorithms, contrast and spatial resolution, artifact induction tolerance, and filters, may supposedly affect their positioning envelope by restricting or extending it. One of the shortcomings of this study is the use of one single CBCT unit, and generalization is therefore difficult. Accordingly, it is suggested that the specific CBCT unit used should be tested in a clinical setting and its operator trained to position the patients within the resulting envelope in order to optimize the accuracy of 3D hard tissue models meant for precise applications. Such an envelope could be made visual in a 3D virtual space for both the operator and patient. Simple alarm systems can be easily built into a CBCT unit that signals when the head position of a patient deviates beyond the predefined error-free positioning envelope with respect to a specifically chosen reproducible position. With the growing recognition of precision medicine by clinicians and patients alike, an individualized error-free positioning envelope customized to different regions of interest and clinical applications will be the next goal worth pursuing. Deviations of head orientation from the RCP are practically unavoidable during acquisition of a 3D craniofacial image from a CBCT unit. Here we determined, for the first time, an error-free head positioning envelope relative to the RCP, beyond which significant and clinically relevant effects on the accuracy of the resulting 3D hard tissue surface model may occur. Moreover, as the effect of head positioning tends to be greater in the maxilla and at lower resolutions, their error-free positioning envelopes are even smaller. It needs to be acknowledged that the RCP was chosen as a zero-deviation position (reference position) because it is one of the most clinically relevant positions and is easy to locate and reproduce with the aid of the built-in laser lines in the CBCT unit. The RCP itself is not necessarily ‘error-free’ in the strict sense, but this is not of importance in the present study as the aim of this study was to define an error-free envelope in relation to a clinically relevant position (RCP) rather than an absolute error-free envelope.

One of the limitations of this study is the absence of soft tissue. With the absence of soft tissue, the segmentation process tends to be much easier and more operator friendly. With soft tissue present the outcomes could differ from the results obtained here. As craniofacial diagnostic and therapeutic procedures in the realm of precision medicine are highly dependent on the accuracy of the 3D surface model, future efforts should be directed to personalize the error-free positioning envelope to different individuals, to various regions of interest, and for specific clinical interventions.

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References

Positioning in CBCT for accurate 3D models


