Dentomaxillofacial Radiology (2005) 34, 28–31

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RESEARCH

Geometric accuracy of the NewTom 9000 Cone Beam CT

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Objectives: To determine the geometric accuracy of digital volume tomograms to assess their usability for implant planning.
Methods: A measuring object with 216 measuring points, whose geometry is exactly known, is X-rayed with a NewTom 9000 cone beam scanner; thereafter the geometry of the volume tomogram of the object is compared with the original body.
Results: Considering all three coordinate axes, geometric mean deviations of 0.13 ± 0.09 mm with a maximum deviation of 0.3 mm were determined. These geometric deviations are below the resolution power of the volume tomograph.
Conclusion: The digital volume tomographies of NewTom 9000 present images which are geometrically correct and, from a geometrical point of view, suitable for three-dimensional implant planning.
Dentomaxillofacial Radiology (2005) **34,** 28–31. doi: 10.1259/dmfr/31342245

Keywords: cone beam CT, digital volume tomogram, geometric accuracy, surgical planning, implant planning

Introduction

The successful use of cone beam scan technique in dentomaxillofacial radiology has been reported for 5 years[1–3] and dosimetric examinations have proved the radiation dose of the cone beam computed tomography (CT) NewTom 9000 (NewTom AG, Marburg, Germany) to be significantly lower than that of other CT imaging methods.[2,4–6] Although cone beam scanners have already been in use for three-dimensional implant planning,[7–9] no clinical trial regarding the geometric accuracy of these scanners has been published until now. It is for this reason that such a test was performed on the NewTom 9000 with an object whose measures were exactly known. The objective of this study was to determine the geometric accuracy of the digital volume tomograms (DVT) made with this machine and thus to obtain information about the reliability of the NewTom cone beam scanner for three-dimensional measuring and surgical planning, *e.g.* implant planning.

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Received 27 July 2004; revised 8 November 2004; accepted 14 November 2004

Materials and methods

A digital volume tomogram was made with the NewTom 9000 of a measuring object (Figure 1). From the volume tomogram a prime data record consisting of individual layers with a distance of 1 mm and pixels with a width of 0.29 mm in x- and y-direction was reconstructed (Figure 2).

The geometric measuring object was a cube with edge lengths of 12 cm. This cube, which was accurate to within 0.01 mm, was made of polymethylmethacrylate. It had 36 openings of 5 mm wide air-filled cylinder bores on each side. This total of 108 cylinder bores formed an orthogonal three-dimensional grid, in which the distance between two cylinder bores in each coordinate axis was exactly 20 mm.

The air-filled cylinders were segmented from the reconstructed data record, and the whole segmented three-dimensional measuring object was placed onto its peak by rotating the x- and y-axes.

The matrices $\mathbf{R}_1$ and $\mathbf{R}_2$ of rotation were used:

$$\mathbf{R}_1 = \begin{pmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 0.71 & -0.71 \\ 0.00 & 0.71 & 0.71 \end{pmatrix} \quad (1)$$

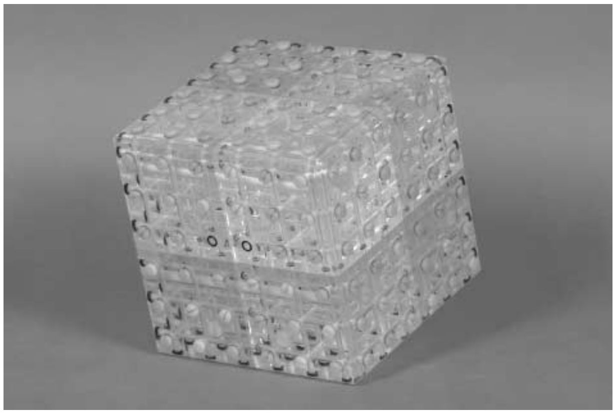

Figure 1 Geometric measuring object with 108 air-filled cylinders and 216 evaluation points

$$\mathbf{R}_2 = \begin{pmatrix} 0.75 & 0.00 & -0.67 \\ 0.00 & 1.00 & 0.00 \\ 0.67 & 0.00 & 0.75 \end{pmatrix} \quad (2)$$

All these reconstructions and vector operations were performed on the SSN++ workstation (SSN, surgical segment navigator; SSN++, second generation SSN system), a navigation and planning workstation for computer-assisted surgery, that is based on a development in our laboratory together with Carl Zeiss, Oberkochen/Germany.[10,11]

Each centre P_i of the altogether 216 cylinder intersections, which was shown as P_i' in the NewTom-data record, was measured.

After placing the measuring object on its peak, each cylinder intersection reveals a star-shaped structure, showing the course of the line of intersection of the three orthogonal tubes with known geometry within a sectional plane of 10 mm slice thickness (Figure 3). A sectional plane of 10 mm of width in which the star-shaped intersection shows the largest expansion was used to determine the centre of the cylinder intersections. For this purpose the star-shaped intersection's best surface matching with an ideal star-shaped intersection of the same size and orientation was determined on the SSN++ workstation (Figure 3).[12]

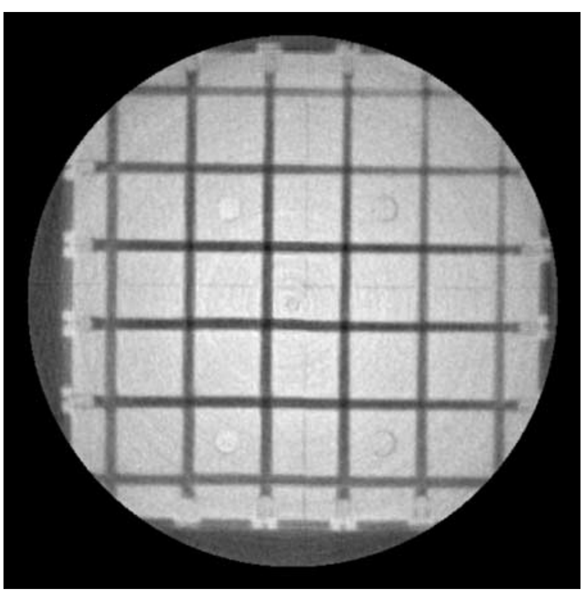

Figure 2 Axial slice of the digital volume tomogram of the geometric measuring object

At the same time the points P_i of the measuring hull were defined as

$$P_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, P_2 = \begin{pmatrix} 20 \\ 0 \\ 0 \end{pmatrix}, P_3 = \begin{pmatrix} 40 \\ 0 \\ 0 \end{pmatrix}, \ldots P_{216} = \begin{pmatrix} 100 \\ 100 \\ 100 \end{pmatrix} \quad (3)$$

with the measuring unit mm in its own orthogonal coordinate system.

As a result, there were two coordinate systems, that is to say, the coordinate system of the volume data record with the points P_i' and the coordinate system of the perfect measuring hull (accurate to within 0.01 mm) with the points P_i. The relation between the coordinate systems was described by

$$P_i' = \mathbf{R} \cdot P_i + \mathbf{t} \quad (4)$$

with a matrix **R** which describes the rotation and a vector **t** which describes a translation. Using an iterative closest point algorithm,[12] the matrix which describes a rotation and the vector which describes a translation were determined. The least squares sum of all corresponding points (P_i with P_i') was determined:

$$\alpha = \Sigma_i |P_i' - (\mathbf{R} \cdot P_i + \mathbf{t})|^2 \quad (5)$$

At the same time the absolute minimum for α was searched for. Thus, all centres of the cylinder intersections served for establishing a reference of the original measuring hull (P_i) to its image in the volume tomogram (P_i'). The distances between each point P_i to its corresponding measuring point P_i' were determined and evaluated (Figure 4).

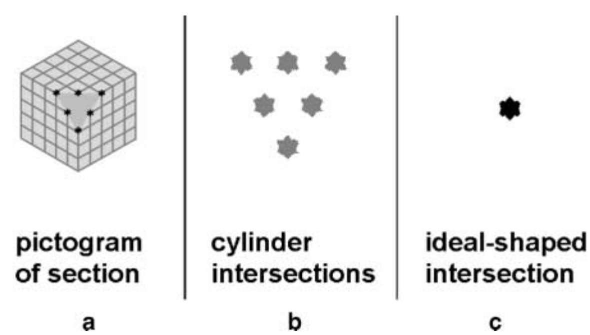

Figure 3 (a) Pictogram of section: top view on the cube, showing one oblique section across the cube; (b) cylinder intersection: cylinder intersections of the corresponding pictogram, revealing star-shaped cylinder intersections within a layer of 10 mm; (c) ideal-shaped intersection: this ideal-shaped object was matched with the cylinder intersections in order to detect the centre of the cylinder intersections

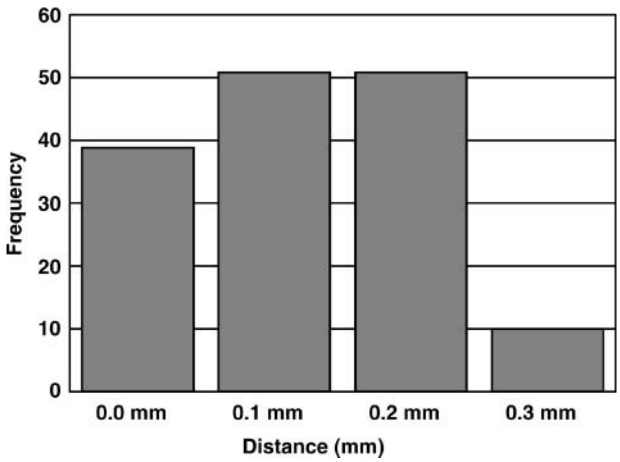

Figure 4 Plot of the frequency of measured distances $|P_i - P_i'|$ of all measuring points

Owing to the above mentioned analysis based on the cube being placed on its peak, δ_{min} was determined to be the minimum relevant measuring difference of the total evaluation:

$$\delta_{min} = \sqrt{\left(\frac{x}{2}\right)^2 + \left(\frac{y}{2}\right)^2 + \left(\frac{z}{2}\right)^2} \qquad (6)$$

whereby $x = y = 0.29$ mm and $z = 1.0$ mm denote the dimension of the quadratic pixels in axial slices and the layer distance, respectively. So the minimum relevant measuring difference was 0.5 mm. Measured deviations below this minimum relevant measuring difference might be due to the resolution of the volume tomogram and to the evaluation procedure, but they do not give proof for a geometric distortion of the volume tomogram.

Results

Only 172 out of 216 measuring points of the original measuring hull were completely represented in the volume tomogram, because the object was somewhat bigger than the scanned volume of the cone beam scanner. The distances $|P_i - P_i'|$ of all measuring points are plotted in Figure 4.

The mean value of all distances was 0.13 mm, with a standard deviation of 0.09 mm. The largest difference was 0.3 mm. Thus, all distances $|P_i - P_i'|$ were below the defined minimum relevant measuring difference of $\delta_{min} = 0.5$ mm.

In the present study no geometric deviations or other non linear distortions were found. Neither was there any accumulation of worse measuring values in certain areas of the measuring object – the measuring values were evenly spread between 0.1 mm and 0.3 mm over the whole reconstructed measuring object.

Discussion

In panoramic radiography examined objects are displayed only two-dimensionally. Therefore there were only other CT imaging methods, involving a considerably higher radiation exposure, available for three-dimensional measuring and surgical planning before the cone beam technique was introduced.[4–6]

Thus, the range of indication for three-dimensional implant planning has been increased by the use of cone beam scanners. However, up to now there had been no study in which the geometric accuracy of cone beam scanners in dentomaxillofacial radiology was examined. It was only Kobayashi who, in 2004, compared volume tomograms of limited cone-beam computerized tomographs with those of spiral computerized CT.[7] In doing so, only small volume tomograms (30 mm wide and 42.7 mm long) were produced, showing deviations of 0.01–0.65 mm to the original object. They did not represent the whole upper and lower jaw as is done by the NewTom 9000.

Considering the whole volume, a larger volume tomogram, as produced in this study, was expected to show even larger geometric deviations than the small volume tomogram of a limited cone-beam computerized tomograph, but this assumption was not confirmed in this study. The determined deviations $|P_i - P_i'|$ of all measuring points were even below the half voxel-space diagonal that was determined to be the minimum relevant measuring difference with $\delta_{min} = 0.5$ mm.

In conclusion, a NewTom 9000 cone beam scanner can produce volume tomograms whose geometric distortion is below the resolution power of the tomograms.

This study is only suitable for the assessment of geometric distortions of the cone beam DVT (NewTom 9000). Spatial resolution, contrast linearity, artefacts from metal objects and software issues in three-dimensional implant planning systems were not considered in the present study.

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