Reliability of CBCT imaging

PhD Thesis

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1. Introduction

The success of interventions affecting the dentomaxillofacial region is determined by the precise and detailed knowledge of the anatomical conditions of the examined area. Among the complementary diagnostical methods, X-ray imaging techniques are widely used. In addition to two-dimensional radiological methods with a history of over one hundred years, the use of three-dimensional imaging techniques, which allows the physician requesting the examination to visualize the given anatomical structure in a given plane of the space, is showing an increasing tendency.

Since the introduction of the first computed tomography (CT) in 1972, three-dimensional imaging techniques have been used in the maxillofacial region. Mozzo et al. have proposed the cone-beam CT (CBCT) device using a cone-shaped beam as a modality for dental imaging, and many publications have since been dedicated to the possible applications of CBCT such as endodontics, implantology, orthodontic interventions, and in other fields such as otolaryngology or skull base examinations.

CBCT imaging causes lower radiation exposure for the patient and allows the production of high-resolution image sequences compared to conventional CT devices. The CBCT device is operating by using a not fan shaped, but divergent, cone shaped X-ray beam and capturing non-overlapping images. From the stored image database, the software of the device produces a series of reconstructed images that can be evaluated in different planes using the image viewer software belonging to the device. However, along with these benefits, as in case of any new method, we need to confirm the reliability of CBCT modality, either *in vitro* or *in vivo*. This can be achieved by a comparative radiological examination of selected anatomical structures or a quantitative measurement of spatial resolution that determines image quality with modalities that have become widely accepted as a reference. In the literature there are currently a limited number of publications available investigating the reliability of the full-length visualization of the root canal system using CBCT imaging technique by the aid of a micro-computed tomography (micro-CT) device, and comparative studies concerning the CBCT and CT imaging modalities in the head and neck region.

2. Aims

2.1. Visualization of root canal systems

2.1.1. Is there a relationship between the voxel size of CBCT devices and the visualization of the entire root canal system?

2.1.2. Might the partial volume effect (PVE) influence the visualization of the root canal's apical level?

2.1.3. Is it possible to use micro-CT as a method of validation for the detection of root canal systems scanned by various CBCT devices?

2.2. Volumetric measurement of paranasal sinuses

2.2.1. Does a three-dimensional CBCT image data CBCT provide reliable information during volumetric measurement of paranasal sinuses, depending on whether the image sequences were made using CBCT or multi-detector CT (MDCT)?

2.2.2. Is there a difference between the volumetric values of paranasal sinuses obtained from InVivo 5.1.2. software by using semiautomatic or hand mode volumetric evaluation, depending on whether the image data was made by using CBCT or MDCT device?

2.2.3. Is there a difference between the volumetric values of paranasal sinuses obtained from InVivo 5.1.2. software by using semiautomatic or hand mode volumetric evaluation?

2.3. Comparative evaluation of spatial resolutions from CBCT and micro-CT

2.3.1. Might be CBCT reliable for depicting submillimetre anatomic structures?

2.3.2. Can micro-CT, as a modality be used to validate depicting submillimetre anatomical structures acquired by a CBCT device?

3. Methods

3.1. Visualization of root canal systems

Three female monkey's (Macaca fascicularis) skulls were scanned by four different CBCT devices: Planmeca ProMax 3D Smart (Planmeca Oy, Helsinki, Finland), Classic i-CAT (Imaging Sciences Intenational, Hatfield, USA), NewTom VG (ImageWorks, New York, USA) and Kodak 9000 3D (Carestream Health, Rochester, NY, USA). The acquisition was taken at the smallest adjustable voxel size for each scanner: 100 µm isotropic voxel size using Planmeca ProMax 3D (84 kV, 10 mA), 250 µm isotropic voxel size for i-CAT Classic (120 kV, 36 mA), 100 × 100 × 150 µm non-isotropic voxel size for NewTom (110 kV, 0.50 mA) and 76 µm isotropic voxel size in case of Kodak (70 kV, 10 mA) device. The software enhancement features available for each device (e.g. metal artefact reduction, adaptive noise filter) were inactivated before the exposition.

On the CBCT images evaluation of the root canal systems was performed by three independent observers in the three planes of the space in coronoapical direction with the aid of the factorial imaging software belonging to the given CBCT device. Two of the observers had more than ten years of experience in endodontics and dental radiology. The left upper second and third molars' mesiobuccal and distobuccal as well as the left lower second and third molars' mesial root canals (12 molars, 24 root canals and one accessory canal) were evaluated. The most apical level, where the root canal lumen was visible on the CBCT images, was used as the reference level (RL) and the observer recorded the distance between the apex and the RL by using the linear measurement tool of the given

image viewer software. During the evaluation of the root canals the observer was permitted to use enhancements and orientation tools on the reconstructed images to improve the image quality for better visualization, for instance adjusting the brightness or contrast. In order to verify the interobserver reliability, the intraclass correlation coefficient (ICC) was determined.
Following CBCT assessments dental jaw sections were prepared containing the second and third molars. The cut-out samples were scanned using SkyScan 1172 microCT (SkyScan, Kontich, Belgium) at a resolution of 17 µm isotropic voxel size, 70 kV tube voltage, 141µA tube current, 4s exposure time and 0.5mm aluminum filter setting. The raw projection images acquired by micro-CT were reconstructed using NRecon v.1.6 software (SkyScan, Kontich, Belgium) with 10 ring artifact correction and 20 % beam hardening correction. The lumen of the root canal was analyzed at the RL, on the cross-sectional image: the area of the lumen, the major and minor diameters, the mean thickness and the aspect ratio of diameters on the reconstructed image sequences using CTAn v.1.1 software (SkyScan, Kontich, Belgium).

3.2. Volumetric measurement of paranasal sinuses

Data of 121 multi-detector CT (MDCT) and 119 CBCT examinations of 240 patients were assessed, retrospectively. The overall mean age was 36,2 years (range: 18-70 years, standard deviation (SD): 16,1 years). The exclusion criteria were as follows: patients with evidence of bone disease (especially osteoporosis); relevant drug consumption; skeletal asymmetries or trauma, congenital disorders, anamnesis of surgical procedures or any pathological disorders involving the maxillary sinuses or the sphenoid sinus. In addition, low-quality images, such as those containing scattering or insufficient accuracy of bony borders, were excluded. In case of MDCT images, 23 right, 28 left maxillary and 11 sphenoid sinuses were excluded; for the CBCT images 23 right, 20 left maxillary and 7 sphenoid sinuses were excluded. In the final study group, all patients were free of any disease and all paranasal sinuses were empty cavities without any pathological conditions. The study protocol was carried out according to the principles described in the Declaration of Helsinki, including all amendments and revisions. The research was authorized by The Regional Scientific and Research Ethics Committee of Semmelweis University (SE TUKEB number: 138/2016.). Only the investigators had access to the collected data.

CBCT scans were performed by using Newtom 3G (Quantitative Radiology s.r.l., Verona, Italy) at an isotropic voxel size of 300 μm by selecting 9- or 12-inch field of view (FOV), 120 kV tube voltage, 3-5 mA tube current. The MDCT images were made by using Philips Brilliance 16 (Philips Medical Systems, Best, The Netherlands) at a 16 × 0,75 collimation, 1 mm slice thickness, 0,688 mm pitch, where the slice thickness of reconstructed image was 1 mm, thus consisting non-isotropic voxels. CBCT as well as MDCT reconstructed image sequences were exported in DICOM file format (512 X 512 matrix) and imported to Invivo 5.1.2 (Anatomage, San Jose, CA, USA) software, then volumetric measurents were performed.

All the reconstructed images were evaluated on a 21.3-inch, flat-panel, active-matrix TFT display (Nio Color 3MP; Barco). The examiner was also permitted to use enhancements and orientation tools such as magnification,

brightness, and contrast to improve visualization of the anatomic structures.
The segmented hard surface representations of the skull of the selected patient were rendered in a virtual scene, whose position was set into a standard position by using a semiautomatic procedure described in a previous study. The volume of maxillary sinuses and sphenoid sinus were evaluated. For the volumetric measurements two modes of the software was used: “hand mode” and “semiautomatic mode.” In case of hand mode, the software performs an inverse image after the program reconstructs a 3D model of the sinus from the DICOM image sequences on which the volume of sinus was selected by cutting out the complementary areas of the air-filled area in the three dimensions manually by using a virtual cutting tool. Then volume measurement was executed by the software.
In semiautomatic mode, we selected at least three points as far apart as possible, so that the two furthest points were located on the boundary of sinus, then the volumetric measurement was run. Statistical analyses were performed by using SPSS v.23 (IBM Corp., Armonk, NY, USA) software. To determine the differences between paranasal volume measurements (age groups, gender and location) Mann-Whitney U-test was used. Differences were considered significant when $p < 0,05$.

3.3. Comparative evaluation of spatial resolutions from CBCT and micro-CT

To determine the MTF, a cylindrical plastic phantom (MicroCT Image Quality Phantom with Slanted Edge, Mediso Ltd., Budapest, Hungary) for micro-CT measurements was used. The phantom containing a cuboid shape slanted edge area in between two air-filled chambers

was placed into a Mediso nanoScan CT micro-CT device (Mediso Ltd., Budapest, Hungary) and fixed with dental wax to the object holder, on which the longer edge of the phantom was perpendicular to the central X-ray beam.The scan was performed by setting the following parameters: 20 µm isotropic voxel size, 70 kV, 720 projections, 300 µA and 300 ms exposure time, binning: 1 X 1, zoom factor: 3.75 X, 1936 X 1936 pixels.
To determine the MTF value of the CBCT device, the phantom was placed in a water-filled cylindrical vessel because the size of FOV to be adjusted was smaller than the size of the phantom. The phantom was placed in the vessel so that the longer edge of the slanted edge area was parallel to the ground plane. To avoid the motion of the specimen, the phantom was fixed to the bottom of the vessel with dental wax and the water-filled vessel was glued to the ground-stabilized metal stage. The phantom was scanned by using Planmeca ProMax 3D CBCT (Planmeca Oy, Helsinki, Finland) at a 100 µm isotropic voxel size (90 kV, 14 mA, 12 s, 501 X 501 pixels). The CBCT and micro-CT raw images were then reconstructed by Feldkamp-Davis-Kress algorithm and exported to DICOM format, which were imported in Mediso Image Quality Center software (Mediso Ltd., Budapest, Hungary). The slanted edge method was used to determine the MTF value of each imaging device. Three adjacent slices were selected on the CBCT and micro-CT images, on which the phantom's transparent, rectangular slanted edge area was visible. On each slice two regions of interest (ROI) were selected along the longer edge of the rectangular area and the software determined the MTF curves and spatial frequency at 10% MTF value.

SPSS software (ver. 23.0.0.0.; SPSS, Inc., Chicago, IL, USA) was used for statistical analysis. Pearson's correlation was performed to determine the correlation coefficient for the spatial resolution of each device.

4. Results

4.1. Visualization of root canal systems

The evaluation of CBCT images was performed in the sagittal and coronal planes most of the cases, since the root canal was the least traceable in the axial plane on the apical level. The performed interobserver reliability test showed a very strong significance (ICC = 0,983; p < 0,001). The possible differences might be due to the fact that although the length of the RLs was found to be consistent, in some cases observers assessed the evaluated root canal visible in the entire length at different rates. In the case of images derived from Kodak CBCT, all root canals were visible along the full length according to the observers', thus no RL could have been determined in any case. Regarding the evaluation of reconstructed images acquired by Planmeca appliance, only one root canal was not detectable in its full length, where RL was 1,80 mm in the coronal direction from the apex. Among the NewTom image sequences in the case of 11 root canals RL was determined by the observers and the mean distance of RL from the apex was 2,79 + 1,34 mm. On the i-CAT images 16 apical levels of root canals were found to be invisible, with a 3.62 ± 1.45 mm mean length of RL-apex distance.

The cross-sectional parameters of root canal lumen on the reconstructed micro-CT images in the axial plane were as follows: the mean area of the root canal 21162 + 14737 μm^2 and 65378 + 65792 μm^2, the major diameter 187,07 ± 82,08 µm and 335,32 ± 210,69 µm, while the mean minor diameter 69,46 ± 43,56 µm and 121,87 ± 86,85 µm on NewTom and i-CAT images, respectively. The aspect ratios representing the cross-sectional shape of the lumen were 3,00 ± 0,98 and 3,11 ± 1,39 and the mean thickness of the root canal lumen at RL was 55,06 ± 18,52 μm and 95.05 ± 44.34 μm for NewTom and i-CAT, respectively.

4.2. Volumetric measurement of paranasal sinuses

The means of the CBCT image-based measurements obtained by hand mode (right maxillary sinus: 14,588 ± 5,644 cm^3, left maxillary sinus: 15,533 ± 5,835 cm^3; sphenoid sinus: 10,059 ± 4,399 cm^3) compared with the previously given sinus volume data from the literature (maxillary sinus: 15 ± 2 cm^3, sphenoid sinus: 12,5 ± 2,5 cm^3) were consistent. However, the volumetric data obtained from the semiautomatic measurements differed from the literature means as they showed significantly lower values (right maxillary sinus: 10,718 ± 4,59 cm^3; left maxillary sinus: 10,403 ± 4,319 cm^3; sphenoid sinus 6,779 ± 3,548 cm^3). Even though the volumetric values of MDCT image sequences obtained by hand mode (right maxillary sinus: 8,074 ± 3,17 cm^3; left maxillary sinus: 8,108 ± 3,258 cm^3; sphenoid sinus: 4,746 ± 2,615 cm^3) compared to the data obtained by the semiautomatic mode were closer, volumetric data derived from MDCT images showed significantly lower values than those obtained from CBCT images. Volumetric values obtained by semiautomatic mode differed from the literature data as they showed significantly lower volumetric means (right maxillary sinus: 5,709 ± 2,52 cm^3; left maxillary sinus: 5,603 ± 2,473 cm^3; sphenoid sinus: 3,104 ± 2,179 cm^3). The volumetric values derived from semiautomatic and hand mode were compared in case of CBCT and MDCT image data. The differences showed very strong significance in each case (p *** < 0,001). The results of volumetric measurements obtained by hand mode on CBCT images were always closer to the literature data.

4.3. Comparative evaluation of spatial resolutions from CBCT and micro-CT

The value of spatial frequency was determined at 10 % MTF value as the limiting spatial resolution of the devices for the selected exposition parameters. The spatial frequencies showed a strong positive correlation in the case of the selected adjacent slices of CBCT and micro-CT images, since the Pearson correlation constant was r = 0,922 and r = 1,000, respectively. Then, the spatial frequency values at 10 % MTF were averaged. The mean spatial resolution of the selected slices of the micro-CT data was 13,35 + 2,47 lp/mm (38,71 + 8,24 μm) and in case of the CBCT data the spatial resolution was at 10% MTF 3,33 + 0,29 lp/mm (150,95 + 11,9 μm).

5. Conclusions

5.1. Only high resolution (≤ 100 μm nominal voxel size) CBCT devices might aid the reliable visualization of the path of a root canal system improving the outcome of the endodontic treatment.

5.2. Partial volume effect might also aid the visualization of the root canal's apical level.

5.3. Since the size of the narrowest root canal was within the range of micro-CT's resolution, consequently micro-CT might be a reliable method for validation in case of *ex vivo* samples for comparing CBCT devices used in everyday clinical practice.

5.4. Three-dimensional CBCT image data provided reliable volumetric information during the volumetric measurements of paranasal sinuses.

5.5. During the semiautomatic and hand mode volumetric measurements – executed in InVivo 5.1.2. software – the volumetric values of paranasal sinuses in case of CBCT data were closer to the previously given literature data compared to the volumetric values of MDCT image sequences.

5.6. The volumetric values derived from semiautomatic mode in InVivo 5.1.2. software showed significantly lower volumes compared to the values derived from hand mode, regardless of whether the image acquisition was made using MDCT or CBCT.

5.7. According to the results of the comparative study of spatial resolution of a CBCT and a micro-CT device we conclude, that the CBCT device on which the adjustable voxel size is 100 μm might aid the proper imaging of submillimetre anatomic structures providing the opportunity for performing reliable micromorphometric analyses.

5.8. Based on our results we concluded, that the visualization of the contour of submillimetre anatomical structures might be even four times more reliable compared to the used high resolution CBCT device.

6. List of own publications

6.1. Publications related to the thesis:

Szabo BT, Pataky L, Mikusi R, Fejerdy P, Dobo-Nagy C. (2012) Comparative evaluation of cone-beam CT equipment with micro-CT in the visualization of root canal system. Ann Ist Super Sanita, 48: 49-52.

Szabo BT, Aksoy S, Repassy G, Csomo K, Dobo-Nagy C, Orhan K. (2017) Comparison of hand and semiautomatic tracing methods for creating maxillofacial artificial organs using sequences of computed tomography (CT) and cone beam computed tomography (CBCT) images. Int J Artif Organs, 40: 307-312.

6.2. Publications not related to the thesis:

Agocs G, Szabo BT, Kohler G, Osvath S. (2012) Comparing the folding and misfolding energy landscapes of phosphoglycerate kinase. Biophys J, 102: 2828–2834.

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Horváthy DB, Schandl K, Schwarz CM, Renner K, Hornyák I, Szabó BT, Niculescu-Morzsa E, Nehrer S, Dobó-Nagy C, Doros A, Lacza Z. (2019) Serum albumin-coated bone allograft (BoneAlbumin) results in faster bone formation and mechanically stronger bone in aging rats. J Tissue Eng Regen Med, 13: 416-422.