Modulation transfer function evaluation of cone beam computed and microcomputed tomography by using slanted edge phantom

BENCE TAMÁS Szabó[1]*, CSABA Dobó-Nagy[1]

[1] Department of Oral Diagnostics, Faculty of Dentistry, Semmelweis University, Budapest, Hungary

*Corresponding Author: Bence Tamás Szabó, 47 Szentkirályi street, Budapest, 1088, Hungary; drszbt@gmail.com

ABSTRACT

Modulation transfer function (MTF) is a well known and widely accepted method for evaluating the spatial resolution of a digital radiographic imaging system. In the present study our aim was to evaluate the MTF obtained from CBCT and micro-CT images. A cylinder shaped phantom designed for slanted-edge method was scanned by a CBCT device at a 100 µm isometric voxel size and by a micro-CT device at a 20 µm isometric voxel size, simultaneously. The MTF curves were calculated and the mean spatial resolutions at 10% MTF were 3.33 $\pm$ 0.29 lp/mm in the case of CBCT images and 13.35 $\pm$ 2.47 lp/mm in the case of micro-CT images. The values showed a strong positive correlation regarding the CBCT and the micro-CT spatial resolution values, respectively. Our results suggests that CBCT imaging devices with a voxel size of 100 µm or below might aid the validation of fine anatomical structures and allowing the opportunity for reliable micromorphometric examinations.

Keywords: Modulation transfer function; Cone-beam CT; Micro-CT; 3-D imaging; Imaging phantom

1. Introduction

Numerous publications have been investigated the use of cone beam computed tomography (CBCT) for evaluating small anatomical structures in dentistry e.g. root canal morphology in endodontics [1-10] or bone quality assessment in maxillofacial surgery [11-20]. It is essential to visualize these details to set up the proper diagnosis and treatment plan, hence clinicians need to select the adequate imaging technique with the appropriate resolution. Among the currently available "high resolution" CBCT equipments the voxel size are 100 µm or even smaller [21], which are comparable with the size of a root canal's apical constriction [22-24] or bone trabeculae [25, 26]. Due to the main advantages of CBCT, namely the higher spatial resolution and lower patient dose compared to medical computed tomography CBCT modality has an increasing interest in the dental practice [27], nevertheless inaccurate image quality can lead to misdiagnosis and unnecessary radiation dose for the patient. Thus it is worthwhile to assess the image quality of the CBCT device and other radiographic imaging system quantitatively to ensure the diagnostic accuracy of the chosen modality [28].

Spatial resolution, which is related to the ability of distinguishing two adjacent structures on a radiograph, is one of the parameters, which can be measured objectively allowing us to estimate the imaging performance of an X-ray based medical system [29, 30]. There are two main methods for determining the spatial resolution, namely visual resolution assessment test and MTF determination. In general both methods are evaluated in line-pairs per millimeter (lp/mm). MTF is a well known and widely accepted method for evaluating the spatial resolution of a digital radiographic imaging system [31, 32]. To calculate the MTF of a computed tomography device thin wire, narrow slit or slanted edge phantom - among others -

can be used, where the MTF is computed quantitatively from the point spread function (PSF) or from the line-spread function (LSF) by using Fourier transform [29, 33-35]. In general the limiting spatial resolution is determined at the spatial frequency level, where the MTF is decreased to 10 % of its maximum value. Brüllmann et al. [29] found in their review, that there is a large variance between the values of observer based visual assessment and the quantitative MTF determination. In addition, numerous studies focusing on MTF measurements as a possible way for quantitatively evaluate the X-ray based imaging devices using cone-beam geometry [28, 30, 33, 35-37]. The image quality and consequently spatial resolution is influenced by several other factors such as focal spot size, overall geometry, tube voltage, tube current, exposure time, rotation arc, the size of field of view (FOV) and the reconstruction parameters as well as the image noise and the movement of the object [7, 29, 37-39]. Rueckel et al. [30] found in their micro-CT study a significant correlation between the focal spot enlargement, which is strongly influenced by the tube power, and the range of magnification: in the case of magnification higher than 30 the gain of spatial resolution is mainly limited by the focus size and less dominant. In a CBCT study Lee et al. [37] concluded that the spatial resolution can be improved by changing the voxel sizes and the reconstruction filters, however the image noise will be increased for smaller voxel sizes. It is important to emphasize that the voxel size given by the manufacturer is a technical parameter, which is not equal to the spatial resolution of the imaging system [29, 40].
In the present study our aim was to evaluate the MTF curves obtained from CBCT and micro-CT images by using a slanted edge phantom and to determine the spatial resolution of the selected devices.

2. Materials and methods

A cylinder shaped plastic phantom (MicroCT Image Quality Phantom with Slanted Edge, Mediso Ltd., Budapest, Hungary) developed for micro-CT measurements was used for determining the MTF values. The phantom consisting of two air-filled chambers and a slanted edge area was placed into Mediso nanoScan CT (Mediso Ltd., Budapest, Hungary) micro-CT scanner and fixed with dental wax to the object holder, on which the longer edge was perpendicular to the rotation axis of the device. The acquisition parameters were as follows: 20 μm isometric voxel size, 70 kV, 720 projections, 300 μA 300 ms exposure time, binning: 1-1, zoom factor: 3.75X, 1936 X 1936 pixels. For the CBCT measurements the phantom was placed into a water-filled plastic cylindrical vessel , since the FOV is larger, than the size of the phantom. The slanted edge area of the phantom was aligned with its longer axis perpendicular to the ground level (Figure 1). To avoid motion artefacts during the scan the phantom was fixed with dental wax to the vessel and the latter was glued to a metal stage, which was stabilized on the ground.

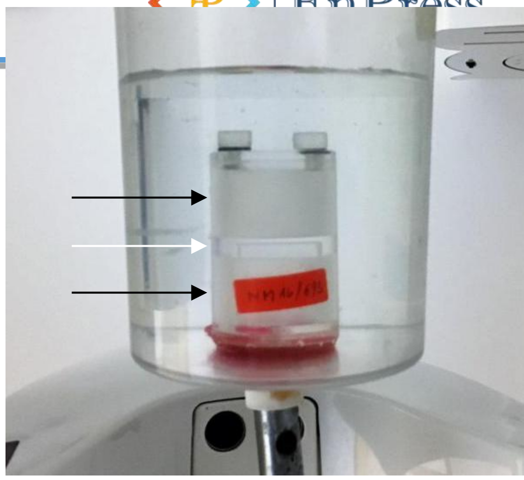

Figure 1. Installation of the phantom with slanted edge before CBCT scan. Black arrows pointing at air filled chambers, white arrow pointing at slanted edge area

The phantom was scanned by Planmeca ProMax 3D CBCT (Planmeca Oy, Helsinki, Finland) at a 100 μm isometric voxel size (90 kV, 14 mA, 12s, 501 X 501 pixels). Thereafter, CBCT and micro-CT datasets were reconstructed by using Feldkamp-Davis-Kress algorithm and exported to DICOM files, then imported into Mediso Image Quality Center software (Mediso Ltd., Budapest, Hungary). Slanted-edge method was used to evaluate the MTF of both devices. From the CBCT and micro-CT reconstructed images three adjacent slices were selected, respectively in which the transparent rectangular shaped area of the phantom was visible. Two different regions of interests were selected at every slice along one of the longer edge of the rectangle (Figure 2) and MTF curves were calculated and spatial frequencies were determined at 10 % MTF by the software. Statistical analysis was performed by using SPSS sofware (ver. 23.0.0.0.; SPSS, Inc., Chicago, IL, USA). Pearson correlation was performed to determine the correlation coefficients (r) for the spatial resolution values of both modalities.

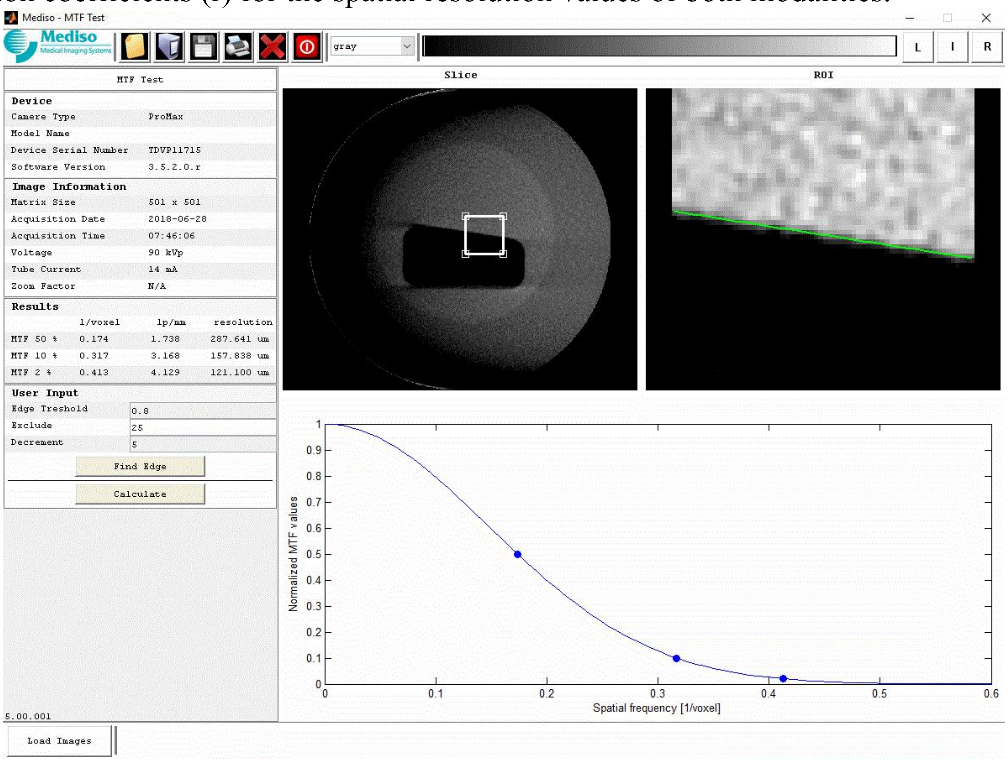

Figure 2. MTF evaluation in Mediso Image Quality Center software

3. Results

The value of spatial frequency was determined at 10 % MTF value for each sample as the limiting spatial resolution of the devices for the selected acquisition 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. Thereafter, 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) In case of the CBCT data the spatial resolution was at 10% MTF 3.33 + 0.29 lp/mm (150.95 + 11.9 µm).

4. Discussion

There is an increasing interest in utilizing the CBCT as a modality in addition to medical applications for imaging fine anatomical structures or even for morphological examinations. Many manufacturers providing the opportunity to adjust the voxel size below 100 µm [21], which allows to assess the reliability of CBCT scanners for depicting submillimeter human anatomical structures.

Micro-CT imaging was already proved to be reliable method [41, 42] for bone micromorphological measurements compared to histomorphometric evaluations, thus numerous researchers apply and cite micro-CT as a high spatial resolution and non-destructive gold standard method [11, 13, 17, 19]. Our measured mean 10 % MTF value was 13.35 lp/mm with 20 µm adjusted voxel size, where a 3.7 Mp detector was used, which is coherent with other findings in the literature: Rong et al. [43] measured 28.2 lp/mm with 12.3 µm voxel size by using a 3,14 Mp detector, while Langner et al. [44] measured at 10 % MTF 22 lp/mm with 15 µm and 6.5 lp/mm with 40 µm sampling, where a 1 Mp detector was applied. Nakaya et al. [35] achieved a 42.4 lp/mm spatial resolution at 10% MTF with 5.87 µm voxel size, however, a 10.5 Mp camera was used in their study. These results suggest, that the adjusted size of the voxel is inversely proportional to the spatial resolution, regarding the 10 % MTF value and, on the other hand, the latter is directly proportional to the size of the detector.

Consequently several comparative studies assessing the image performance of the CBCT devices with micro-CT as a possible tool of validation [11, 13, 15-20, 45]. Considering our results, the measured 38.71 µm mean spatial resolution of the micro-CT images provides micromorphologically reliable images, since the spatial resolution is smaller, than the scanned human anatomical structure such as human cancellous bone, in which the trabeculae have a dimension of 50 - 300 µm [16, 46]. Liang et al. [13] assessed two human condylar region of the mandible scanned by CBCT and micro-CT devices, simultaneously. They determined the mutual information values after registering the images and concluded that the assessments of mandibular trabecular structures by using CBCT scanner are comparable with the results of the assessments, where micro-CT was used for image acquisition. These statements are supported by Ibrahim et al. [16], who compared trabecular thickness (Tb.Th), trabecular separation (Tb.Sp) and trabecular number (Tb.N) micromorphometric parameters, of which only Tb.N was underestimated in the CBCT image sequences in contrast to Tb.Th and Tb.Sp, which were found to be greater comparing with the micro-CT datasets. Additionally, Parsa et al. [17] measured the percent bone volume (bone volume (BV)/tissue volume (TV)) on datasets obtained by micro-CT and CBCT devices and the values of the latter proved to be greater. These findings are in accordance with the findings of Kim et al. [19], who found BV/TV values to be greater on CBCT dataset, among others such parameters as BV, Tb.Th and Tb.Sp, compared to the measurements obtained from micro-CT. Van Dessel et al. [11] concluded in their comparative evaluation of seven CBCT and one micro-CT devices, that CBCT devices with voxel size of 100 µm or below might be reliable for morphometric measurements regarding the structural pattern of the alveolar bone. If a same-sized object is scanned by a CBCT device and a micro-CT device, it is expected to be depicted in an extended volume on the CBCT images compared to the micro-CT images most probably due to the partial volume effect, as a possible explanation. Or even if the reconstructed image volume is larger than the real size of the scanned object, the pattern of the depicted bone area is proved to be comparable with the datasets obtained by a micro-CT device [11, 16, 17, 19].

Another possible clinical application of the CBCT modality is the three-dimensional visualization of the dental root canal. Yilmaz et al. [8] concluded that CBCT image sequences with less than 300 µm voxel size can be used for determining the working length during an endodontic treatment of a human mandibular premolar tooth. Nonetheless Acar et al. [3] found no correlation by comparing the CBCT and micro-CT image sequences of 41 human primary first and second molars regarding the detectability of an accessory canal and stated that CBCT is not reliable for depicting the internal anatomy of a root canal system. These findings are in line with our previous study [10], where the accuracy of three different CBCT devices was compared with micro-CT by assessing 25 root canals of three monkeys' skull. According to our results it was stated that the full length of a root canal can be detected only on CBCT images, if the selected voxel size is adjusted to or below 100 µm, however, the real contour of the root canal cannot be determined. These findings suggest, that there might be a correlation between the accuracy of the CBCT and micro-CT modalities. The apical ending of a root canal, where the diameter of the physiological foramen of a human molar tooth varies between 79 -720 µm [24]. At this level CBCT images are not capable to give anatomically faithful information due to the fact, that the physiological foramen can be smaller than the adjustable smallest pixel size, though the partial volume effect might aid the visualization of the root canal's path only, but not the exact shape or the contour of the root canal [10].

Our present study verifies that micro-CT image sequences provide accurate information in the range of the human tissues (e.g. cancellous bone, root canal). However, the measured values of spatial resolution for both modalities are comparable with the average trabecular thickness size of the human trabeculae or the diameter of the apical ending of a root canal [22-24], which suggests that CBCT as well as micro-CT might aid the valid visualization of these structures either in vivo or ex vivo studies, respectively.

5. Conclusion

Our findings suggests that CBCT imaging devices with an adjustable voxel size of 100 µm or below might aid the validation of fine anatomical structures and provide the opportunity for reliable micromorphometric examinations.

Conflict of Interest

No conflict of interest was reported by the authors.

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