CT numbers of CBCT regarding position dependence on different size of field-of-view

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Authors: M. Imura¹, T. Todoroki²; ¹Kyoto/JP, ²Osaka/JP
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Purpose

CT numbers of CBCT regarding to position-dependence on different size of field-of-view

Minori Imura & Takeshi Todoroki
Kyoto, JAPAN

Table 1

References: M. Imura and T. Todoroki; Kyoto, JAPAN

CT number is expressed in Hounsfield units (HU), which provide a standard scheme for scaling a converted value of photon quantity that is proportional to attenuation coefficient in multi-detector row computed tomography (MDCT). CT number is devised to ensure the compensation for the reduction of X-ray intensity from the focus to the detector, and is quality assured by various corrections such as spatial and temporal stability and reproducibility.

Despite of its compact design and better spatial resolution (1) over MDCT, cone beam computed tomography (CBCT) was not able to display CT numbers as in MDCT; because of less X-ray intensity, less intake ray numbers, scattered ray effect or differences of reconstruction algolrism. As for CBCT, a number of studies have been tried to deliver HU over many years. A conversion value of the gray shade gradation of the images on a monitor was named such as voxel value, gray scale value or intensity value, and was
assigned for each pixel. These values had been dealt with as if they were CT numbers (2-5). However, those values varied (6-12) and were not reproducible because the values relied on the gradation limited to the inside of the displayed area on the monitor.

Recently, Quality controlled X-ray beam CBCT (QX-CBCT) has been introduced. QX-CBCT is a dental CBCT with calibration function for HU scale in cone beam CT for the first time. This CBCT is totally different from conventional CBCT, in that CT numbers are derived from relative absorbance of X-ray photon of a given subject same as MDCT. To execute CT number display, QX-CBCT has following unprecedented features. The focus detector distance (FDD) of conventional CBCT is less than 650 mm, and the focus intercentre distance (FID) is almost half of the FDD, resulting in that the subject is positioned at the almost center of FDD. To secure maximum irradiation field by this geometry, the projection data is acquired disregarding the effect of scatter X-ray or the effect of spreading beam from effective focal spot, namely heel effect. Thus, it is impossible to deliver CT number same as MDCT (13) by reconstructing the projection data which is affected the above factors. On the other hand, of the geometric construction in QX-CBCT, FDD and FID is longer as 895 mm and 625 mm respectively, resulting in the ratio of FID to FDD is much more than half. This longer FID is more advantageous geometry than conventional CBCT to reduce cone and fan angle (Fig. 1 on page 4) as well as to reduce the penumbra on same size of irradiation field (Fig. 2 on page 4). Regarding to the cone angle, in addition to the geometric merit, X-ray beam is trimmed in order to reduce heel effect; limited to 10 degrees cathode side from native beam center of the cone angle where more uniform X-ray intensity area is utilized. On top of these technologies, bow-tie filter is equipped in order that direct beam X-ray intensity after passing through the object to be uniform. Regarding to the image reconstruction, dedicated DFK algorithm contributes to reproduce exact three-dimensional information of scanned object by means of reducing distinctive cone beam artifact, as well as serves HU scaling by unique correction for the focus-each detection element distance and incident angle. Other than those technologies, calibration system for panel, geometry, and Hounsfield Units, in addition to quality-check system of spatial resolution, noise and mean CT number uniformity, are applied. By those unique technologies, CT numbers are become available for the first time in CBCT.

In this study, we examined the characteristics of CT numbers in QX-CBCT in terms of cone beam effect and scan filed of view.
Fig. 1: Concept illustration of an impact of geometry of QX-CBCT. Wider FDD (white arrow line) and longer FID (blue arrow line) than conventional CBCT are advantageous geometry for smaller cone and fan angle, resulting in less cone beam artifact.

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Fig. 2: Concept illustration of an impact of longer FID for penumbra. Wider FDD (white arrow line) and longer FID (blue arrow line) are also advantageous to reduce the penumbra (red longitudinal arrow line) for same irradiation field in comparison to conventional CBCT. Note the differences of the red longitudinal arrow line and rhomboid dots on the detectors.

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Methods and Materials

Instrumentation and Imaging parameters

All CBCT images were obtained by WhiteFox (Acteon group Satelec)

Scan parameters

The scan parameters for CBCT system were: maximum emission of typical 48 mAs/exam, tube voltage of 100 kV, anodic current of 9 mA, scan time of 9 sec (high exam quality), sampling trajectory of one rotation 360°, and reconstruction section thickness of 0.5 mm. The size of field of view (FOV) were 60 mm x 60 mm x 60 mm (HA), 80 mm x 80 mm x 80 mm (DA), and 120 mm x 120 mm x 80 mm (BDE) (Fig. 3 on page 9).

The scan parameters for 64-row MDCT system were: tube current of 350 mA fixed, rotation time of 0.5 second, beam collimation of 20 mm, table feed per rotation of 27.5 mm, beam pitch of 1.375:1, field of view of 13 cm, reconstruction section thickness of 5 mm with no overlapping, reconstruction type of standard, pixel matrix size of 512x 512, and total range of 16 bits.

Phantoms

Water phantom attached to QX-CBCT for calibration, whose diameter is 16 cm same as QA phantom for head and neck of MDCT, was used to evaluate CT number in QX-CBCT (Fig. 4 on page 9). Seventeen different iodine concentration solution homemade phantoms of 0 to 4700 HU adjusted by MDCT at 120 kV tube voltage were used to assess correlations of CT numbers between QX-CBCT and MDCT.

Tube voltage measurement

Peak and mean tube voltage of both QX-CBCT and MDCT were measured by non-invasive X-ray Output Analyzer.

Evaluation of reproducibility and region-dependence of CT number in QX-CBCT on three sizes of FOV
Water phantom attached to QX-CBCT for calibration was scanned repeatedly. Twenty-one, twenty-nine and sixty-one ROIs of 0.202-cm\(^2\) on each axial image were placed for HA, DA and BDE respectively, and mean CT number of each ROI were measured (Fig. 5 on page 10 left).

**Investigation of reproducibility**

We examined the reproducibility of the mean CT number of each ROI between scans on each FOV, as well as the reproducibility of each ROI of corresponding place on different FOV.

**Investigation of region-dependence**

To investigate the region-dependence of CT numbers in QX-CBCT, vertical and horizontal uniformity profiles on three sizes of FOV were examined. Each axial slice was concentrically divided into five, seven and fifteen sections for DA, HA and BDE respectively (Fig. 5 on page 10 right). Integral non-uniformity index, as well as uniformity index was calculated from the mean CT number of ROI at the center and four peripherals of each section. Integral non-uniformity index was defined as \((CT_{max} - CT_{min}) / (CT_{max} + CT_{min})\), and uniformity index was defined as \(100 \times (CT_{periphery} - CT_{center}) / CT_{center}\) (14).

**Evaluation of the correlations of CT numbers between QX-CBCT of three sizes of FOV and MDCT**

To assess correlations of CT numbers between QX-CBCT and MDCT, seventeen different iodine concentration solution phantoms of 0 to 4700 HU were scanned at 100 kV for QX-CBCT and at 80,100,120,140 kV for MDCT.

On the basis of the result from region-dependence of CT number in QX-CBCT, we measured mean CT number of the central 50 mm slices with 4-cm\(^2\) ROI. Correlations of CT numbers between QX-CBCT for three FOV and MDCT were examined.

**Measurement of CT number**
All CT numbers were measured by open-source DICOM viewer, Osirix 3.0 system. For QX-CBCT, ten of reconstructed 0.5 mm thick slice were overlapped to be 5 mm thick, same slice thickness as MDCT to compare CT numbers.

**Statistical analysis**

Pearson’s correlation coefficient was calculated to assess the reproducibility of CT number in QX-CBCT as well as correlation of CT numbers between QX-CBCT and MDCT. Friedman Test (Nonparametric Repeated Measures ANOVA) was also performed to examine the differences of the mean CT number of the ROI for corresponding place on three different FOV.
**Fig. 3:** Cartoons of the position and the size of HA, DA and BDE in the calibration phantom of QX-CBCT. The most outer (largest) cylinder is the calibration phantom of QX-CBCT. FOV of HA, DA and BDE are most inner smallest cylinder, middle cylinder and rectangular parallelopipded, respectively.

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**Fig. 4:** QX-CBCT and its calibration phantom. The diameter of the calibration phantom of QX-CBCT is 16 cm, same as QA phantom for head and neck of MDCT.

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**Fig. 5:** ROIs for evaluation of reproducibility and region-dependence of CT number in QX-CBCT on HA, DA and BDE. Integral non-uniformity index and uniformity index were calculated by the center (A1) and the peripherals of each section. For example, ROI of A1, B2, C2, D2, and E2 were used to calculate integral non-uniformity index of section 2 (red dot circle on the right).

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Results

Reproducibility and region-dependence of CT number in QX-CBCT on three sizes of FOV

Reproducibility of CT number between scans on each FOV

Correlation coefficients of each independent ROI on each of three FOV were statistically significant. (R = 0.95, P < 0.0001, R = 0.91, P < 0.0001 and R = 0.90 P<0.001 for HA, DA and BDE respectively).

Reproducibility of CT number of ROI for corresponding place on different FOV

Correlation coefficient of the mean CT numbers of the ROI for corresponding place on different FOV exhibited statistically significant (R = 0.92, P < 0.01), and the values of the ROI on different FOV were not significantly different.

These results indicate that the mean CT numbers at each ROI on each FOV, as well as the mean CT number of the ROI for corresponding place on different FOV, in QX-CBCT are highly reproducible.

Region-dependence

Figure 6 and 7 show horizontal and vertical profile of Integral Uniformity index, CT numbers and uniformity index of DA. The horizontal profile (Fig. 6 on page 15) is of center slice direction 1 and 2, and vertical profile (Fig. 7 on page 15) is of section1 and ROI C1. Integral uniformity index at the central region were relatively constant, whereas the CT numbers and uniformity index were fluctuate. We also noticed that the length of the central constant area of integral non-uniformity index exhibited position-dependence on both horizontal and vertical profiles: the further from the center, the shorter the length of the constant area was (data not shown).

Fig. 8 on page 16 shows the central horizontal and vertical profiles of integral non-uniformity index of HA, DA and BDE. The horizontal profile is of center slice direction 1 and vertical profile is of section1. The values of integral non-uniformity index of three FOV were close, and the tendency of fluctuation was similar as relatively constant at the central region compare to outer edge. On both horizontal and vertical profiles, the length of relatively constant region was approximately 50 mm at most at the center for all three
FOV, and exhibited position-dependence as the further the distance from the center was, the shorter the length was (data not shown).

These results indicate that the central 50 mm region is relatively uniform on three FOV.

MIP image of the water phantom of BDE is shown on Fig. 9 on page 17. The shape of the central region was sphere-like.

Taken together, these results indicate that although the CT numbers of QX-CBCT are reproducible for each ROI, there exists inter-slice and intra-slice fluctuation, which are greatly different from those of MDCT (15). The central approximate 50 mm area is relatively uniform regardless of FOV, and this length would correspond to the diameter of sphere-like region that was observed in MIP (Fig. 10 on page 18).

**Fig. 10:** Concept illustration of relatively uniform area. The length of the relatively constant area of integral non-uniformity index at the center of vertical (red line) and horizontal (blue line) profiles would correspond to the diameter of sphere-shaped region.
Correlations of CT numbers between QX-CBCT of three sizes of FOV and MDCT

Fig. 11 on page 19 shows the CT numbers of three FOV on QX-CBCT and MDCT. CT numbers of QX-CBCT were highly correlated with those of MDCT under 2500HU, whereas the values lost its linearity over 2500HU. For the evaluation of correlation, phantoms over 2500HU were excluded since SD of the both CBCT and MDCT images were over 30 by lacking of X-ray intensity. Correlation coefficients of each FOV in QX-CBCT and MDCT under 2500 HU were statistically significant. (R = 0.997, P < 0.0001, R = 0.98, P < 0.0001 and R = 0.97 P<0.001 for HA, DA and BDE respectively). However, the values were not identical.

Tube voltage of QX-CBCT

Mean Tube voltage of QX-CBCT was 100 kV.
Fig. 6: Horizontal profile of CT number, integral non-uniformity and uniformity index of DA. Integral non-uniformity index (yellow line) and CT number (green line), and Uniformity index (blue line) at the center slice. Direction 1 and 2 are shown on the left and the right, respectively. Integral non-uniformity index at the central region are relatively constant, whereas the CT numbers and uniformity index are fluctuate.

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Fig. 7: Vertical profile of CT number, integral non-uniformity index and uniformity index of DA. Left: Integral non-uniformity index of section1 (yellow line), CT number of ROI A (green line), and Uniformity index (blue line) of ROI C1. Right: The sagittal image. Similar to horizontal profile, integral non-uniformity index at the central region are relatively constant, whereas the CT numbers and uniformity index are fluctuate.

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Fig. 8: Horizontal and vertical profiles of integral non-uniformity index on HA, DA and BDE. Top: Horizontal profile of direction 1 at the center slice. Bottom: Vertical profile of the center region of each axial slice, section 1. The values of three FOV are close, and are relatively constant at the central region compare to those of the outer edge.

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**Fig. 9:** MIP image of the water phantom of BDE. Left: Axial, sagittal and coronal views are shown on the top, middle and bottom, respectively. Right: 3D image. The shape of the central region is sphere-like shape.

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**Fig. 10:** Concept illustration of relatively uniform area. The length of the relatively constant area of integral non-uniformity index at the center of vertical (red line) and horizontal (blue line) profiles would correspond to the diameter of sphere-shaped region.

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Fig. 11: CT numbers of MDCT and QX-CBCT. CT numbers of QX-CBCT on HA, DA and BDE significantly correlate to those of MDCT under 2500 HU (R = 0.99 P < 0.0001, R = 0.98 P < 0.0001 and R = 0.97 P < 0.001 for HA, DA and BDE, respectively), whereas the values lost its linearity over 2500 HU.

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Conclusion

QX-CBCT is a novel CBCT which equipped with calibration function for HU scaling. This photon quantity derived CT number has become available by unprecedented unique technologies that were not with conventional CBCT. We have previously reported that CT numbers of QX-CBCT were reproducible but exhibited region-dependence in irradiation field at 60 mm x 60 mm (16). In this study, we examined the characteristics of its CT numbers for different size of FOV.

In our first results, the mean CT numbers of the center region, when assessed by Integral uniformity index, were relatively uniform regardless of the size of FOV, and this relatively uniform area could be sphere-like shape. These results are likely to be reflecting cupping artifact by scatter radiation. In the literature, it was reported that scatter radiation intensity of CBCT after passing though the middle portion of a uniform cylindrical phantom was about twice as much as the direct beam intensity (17). Since the CT numbers of QX-CBCT are derived from photon quantity at the detector, the sum of direct beam and scatter radiation are reflected. Relative quantity of scatter radiation at the middle portion of a water cylinder phantom were more than those of the edges, resulting in that the CT numbers across the phantom displayed a characteristic cupped shape in reconstruction (18, 19). We observed this phenomenon as a sphere like shape by maximum intensity projection (MIP).

We next demonstrated that the mean CT numbers at the center region were highly correlated to those of MDCT regardless of FOV, however, the values were not identical to those of MDCT. The underlying causes of the observed differences of the mean CT numbers between QX-CBCT and MDCT are likely to be the inherent differences of CBCT and MDCT as followings. The X-ray beam of CBCT and MDCT are both continuous spectrum (20, 21) which cause various influences such as beam hardening effect, scatter radiation or partial volume effect. Consequently, CT numbers are relative absorbance of X-ray photon of a given subject. However, CBCT was developed separately from MDCT. Cone beam X-ray results in un-uniformity of X-ray between the anode and the cathode, so called heel effect. Dynamic range of the detector is 12 -14 bits, which is not sufficient in contrast to 16-18 bits of MDCT. Flat panel detector as well as much less X-ray energy than MDCT cause more prone to scatter radiation (19). In addition, the number of projections of MDCT is 1000 views per rotation, whereas that of CBCT is only 270 rays per rotation which causes streak artifact. Instead of convolution back projection (CBP) method for MDCT, FDK algorithm is adopted for image reconstruction of CBCT to reappear three-dimensional information of scanned object. Image reconstruction by FDK algorithm is more prone to the artifact by the X-ray absorbing objects outside of FOV (22, 23). In QX-CBCT, dedicated FDK algorithm, in which incident angle as well as the focus-each detection element distance is individually corrected, is adopted. However, it is still
insufficient to avoid the influence of beam hardening or scatter radiation. Consequently, the uniformity same as MDCT was unattainable.

In the future, it could be possible that the CT number of QX-CBCT would be more uniform by various technological improvements such as direct beam correction for Z axis by three-dimensional (sphere like shaped) bow-tie filter, computational intensive beam hardening correction, increase of the number of projections, reconstruction algorithm more advanced than FDK, or reduction of scatter radiation as well as securing direct X-ray intensity more than scatter radiation. However, it would be a hard task to attain same accuracy as MDCT considering various X-ray effects due to inherent differences of CBCT and MDCT. Therefore, the CT number of QX-CBCT, although it is derived from photon quantity, should be handled as a different value to that of MDCT. Standard criteria or reference would be an important future issue because there is a possibility that photon quantity derived CT number of CBCT and its position dependence will be variable for every machine; variety of the size of FOV and/or X-ray intensity resulting in the differences of the artifacts such as scatter radiation or beam hardening. In fact, we could demonstrate the characteristics of CT numbers of QX-CBCT, however, we have no references to evaluate whether those values were "appropriate" or not. Currently, there is no other CBCT than QX-CBCT that is able to derive CT number from photon quantity like MDCT, it would be possible to establish the reference of the CT number of CBCT by using QX-CBCT. In this study, we used attached water phantom whose diameter is 16cm, same size as quality assurance (QA) phantom for head and neck of MDCT. But to establish reference, QA phantom dedicated to CBCT would be required in the future (24, 25).

In conclusion, mean CT numbers of QX-CBCT were reproducible for all three FOV. Mean CT numbers at the center region were relatively uniform regardless of the size of FOV, and highly correlated to those of MDCT. However, due to cupping effect, the larger the FOV was, the more un-uniform CT numbers at the outer edge were observed. Therefore, when handing the CT numbers of QX-CBCT, region-dependence within irradiation field due to the effect of cone beam should carefully be considered. For clinical use, target region is better to be positioned at the center of FOV. In near future, further better accuracy of CT number of QX-CBCT, establishment of its reference, as well as effective usage of those values in clinical field is expected.
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Thank you for your interest in this exhibit. If you have any question or comment, please contact me via email (minori.imura@gmail.com).

Takeshi Todoroki, MRT Table 2 on page 27
todoroki.takeshi@gmail.com

The authors would like to express our gratitude to our family for their moral support and warm encouragements.

Table 2
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