Technical versus diagnostic image quality in dental CBCT imaging

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Purpose

The diagnostic image quality of dental CBCT has been extensively studied in vitro and in vivo. [1-6]. Different skull and jaw models are used which limits the standardization and intercomparison of quantitative image quality measurements, and findings from these studies are often limited to the investigated type(s) of scanner. Alternatively, geometrical phantoms have been used to investigate technical image quality parameters [7-9]. The limitation of using technical image quality parameters as reference levels for clinical practice is that there is no straightforward way of translating these parameters to diagnostic relevance. Whether or not an image is acceptable for clinical purposes is determined by the observer of the image, adding another degree of subjectivity to the use of CBCT [10-13].

The aim of this study was to investigate image contrast, noise and diagnostic image quality at various exposure levels for different dental CBCT scanners, to determine the relationship between technical and clinical imaging parameters, and to define preliminary thresholds or reference levels for CBCT image quality.
Methods and Materials

CBCT devices

Four CBCT devices were included in this study: 3D Accuitomo 170 (J. Morita, Kyoto, Japan), CRANEX 3D and SCANORA 3D (Soredex, Tuusula, Finland), and Galileos Comfort (Sirona, Bensheim, Germany). Exposure parameters are listed in Table 1. A total of seven imaging protocols, determined by the FOV size and voxel size, were selected. For the 3D Accuitomo 170 and SCANORA 3D, a small and large FOV size with varying voxel size was selected. For the CRANEX 3D, a high- and low-resolution protocol was selected for the largest available FOV. For the Galileos Comfort, only the mAs was varied as the FOV and voxel size is fixed. The full available mAs range was included for each imaging protocol with the exception of the 3D Accuitomo 170, for which the highest mAs values were discarded for the observer study as they are up to 100% higher than clinically used mAs settings.

Technical image quality

A head size PMMA phantom (16cm diameter) was used for the analysis of contrast and noise. The phantom is homogeneous with the exception of a central air hole of 10mm diameter at the bottom. As this air hole was needed for contrast analysis, the phantom was placed on a second PMMA phantom, allowing for the bottom part to be scanned without interference from supporting structures (e.g. metal platforms).

All datasets were exported as axial slices in DICOM format and evaluated with ImageJ software version 1.41o (National Institutes of Health, Bethesda, MD, USA). All measurements were performed by two researchers.

Contrast-to-noise ratio (CNR) was measured between the air hole and the PMMA by measuring the mean grey value and standard deviation for both materials, and using the following calculation:

\[ \text{CNR}_{\text{AIR}} = \frac{MGV_{\text{PMMA}} - MGV_{\text{AIR}}}{\sqrt{(SD_{\text{PMMA}}, \text{Voxel}^{0.608})^2 + (SD_{\text{AIR}}, \text{Voxel}^{0.608})^2}} \]

Fig. 9

References: - Leuven/BE
with MGV the mean grey value, SD the standard deviation, and Voxel the voxel size of the image. To calculate the correction factor for voxel size, raw projection data from the 3D Accuitomo 170 was reconstructed at varying voxel sizes, allowing for the power factor for the inverse relation between voxel size and noise to be quantified. It should be noted that, even though dental CBCT images use varying bit depths, no grey value range correction was needed, as the CNR calculation itself takes the grey value range into account.

**Diagnostic image quality**

An anthropomorphic skull phantom (RANDO, The Phantom Laboratory, Salem, NY, USA) containing a human skeleton embedded in polyurethane was used (Figure 1). The phantom represents an adult male (175 cm tall; 73.5 kg), and consists of a human skull with full dentition, embedded a soft tissue-equivalent material (i.e. polyurethane) simulating muscle tissue with randomly distributed fat. The natural human skulls are adjusted to correct for a natural lack of symmetry. For each dataset, 8 axial slices and one coronal slice with relevant anatomical landmarks were selected and combined in a stack for the convenience of the observer.

Six experienced oral radiologists were selected as observers. Using ImageJ, a total of 47 stacks each consisting of 9 selected slices was scored. The observers were allowed to adjust brightness and contrast, and instructed to fine-tune grey level display for optimal visualization of the different anatomical landmarks, rather than using a single window/level setting for the entire evaluation. The visualization of ten different anatomical landmarks was scored: mandibular symphysis, mental foramen, cortical bone, lamina dura, periodontal ligament (PDL) space, pulp canal, enamel, maxillary structure, incisive foramen and trabecular bone. For all landmarks which are present in both jaws (e.g. trabecular bone), a separate score for upper and lower jaw was provided. In addition, the observers provided a score expressing the usefulness of the image for three clinical applications: root pathology, sinus pathology and implant planning. For all evaluations, a 4-point rating scale was used, summarized in Table 2. Inter-observer agreement was estimated using a weighted kappa, calculated with MedCalc (version 11.2, MedCalc Inc., Mariakerke, Belgium).

The relation between mAs, noise, CNR and observer scores was evaluated. Based on the threshold score of 2.5, being the limit between acceptable and unacceptable image quality for the three clinical applications, the corresponding CNR levels were determined as preliminary reference levels. Addtional reference levels were defined as the minimum CNR value for which scores for all observers was 3 or higher.
**Table 1: CBCT devices and exposure parameters**

<table>
<thead>
<tr>
<th>CBCT</th>
<th>FOV</th>
<th>Voxel size</th>
<th>kV</th>
<th>mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Accuitomo 170</td>
<td>14x10</td>
<td>0.25</td>
<td>90</td>
<td>18-123</td>
</tr>
<tr>
<td></td>
<td>6x6</td>
<td>0.125</td>
<td>90</td>
<td>18-123</td>
</tr>
<tr>
<td>SCANORA 3D</td>
<td>13.5x14.5</td>
<td>0.35</td>
<td>90</td>
<td>11-17</td>
</tr>
<tr>
<td></td>
<td>6x6</td>
<td>0.2</td>
<td>90</td>
<td>12-39</td>
</tr>
<tr>
<td>CRANEX 3D</td>
<td>6x8</td>
<td>0.2</td>
<td>90</td>
<td>56-139</td>
</tr>
<tr>
<td></td>
<td>6x8</td>
<td>0.3</td>
<td>90</td>
<td>29-63</td>
</tr>
<tr>
<td>GALILEOS Comfort</td>
<td>15x15</td>
<td>0.29</td>
<td>85</td>
<td>10-42</td>
</tr>
</tbody>
</table>

**Table 2: Rating scale for observer study**

<table>
<thead>
<tr>
<th>Score</th>
<th>Anatomical landmarks</th>
<th>Usefulness for clinical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very poor visibility</td>
<td>Certainly not useful</td>
</tr>
<tr>
<td>2</td>
<td>Poor visibility</td>
<td>Probably not useful</td>
</tr>
<tr>
<td>3</td>
<td>Acceptable visibility</td>
<td>Probably useful</td>
</tr>
<tr>
<td>4</td>
<td>Excellent visibility</td>
<td>Certainly useful</td>
</tr>
</tbody>
</table>

**Table 2: Rating scale for observer study**

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Figure 1 RANDO phantom, head and neck portion

Fig. 1: RANDO phantom, head and neck portion

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Results

Scatter plots for CNR versus mAs are provided in Figure 2. For the 3D Accuitomo 170, a clear hyperbolic relation is seen as this device allows for the selection of a wide mA range, with a 10:1 ratio between the highest and lowest exposure. For the other devices, either a curved or linear section of a hyperbolic relation is shown as the mAs ratio between the highest and lowest exposure is smaller (SCANORA 3D: 3.1:1, CRANEX 3D: 2.2-2.5:1, GALILEOS Comfort: 4.2:1).

Selected axial slices for each exposure protocols at the level of the mental foramen and maxillary bone are shown in Figures 3 and 4, respectively. For each FOV/resolution protocol, the default mAs for dental clinical scanning was selected for these figures.

Kappa values representing intra-observer agreement were between 0.336 and 0.677 with an average of 0.469 (Table 12.3).

Figure 5 demonstrates the relation between the CNR and the average observer score for all parameters. To calculate this average, values for mandible and maxilla (e.g. cortical bone) were first averaged before averaging with the other parameters. Considering a score of 2.5 as threshold value between an acceptable or unacceptable image (Table 2), most exposure protocols show an acceptable average score, even for the lowest mAs setting. Two exposure protocols dropped below this threshold for lower mAs values due to low scores for the mandibular symphysis, PDL space and lamina dura.

The highest score for all anatomical parameters was for the mental foramen, for which all scores were above the 2.5 mark. The maxillary lamina dura had the lowest score for all parameters (Figure 6). Difference between score for maxilla and mandible were highest for the cortical bone, for which the maxilla received a lower score (Figure 7). The difference between scores for maxilla and mandible were largest for the GALILEOS Comfort and lowest for the 3D Accuitomo 170, small volume (Table 4).

Figure 8 shows the scores for the three clinical indications. Similar to the anatomical landmarks, a score of 2.5 corresponds to the threshold between an image that is suitable for the given clinical indication, and one that is not.

Table 5 shows observer scores for all anatomical parameters. For all seven exposure protocols, the minimum and maximum score (i.e. scores for the lowest and highest mAs, respectively) for the fifteen anatomical landmarks is provided. Table 6 contains the minimal mAs level for which the scores for the three clinical indications was above the
2.5 threshold, as well as the corresponding CNR value. Also included in Table 6 is the minimal mAs value for which the score was 3 or more for each observer for the three clinical indications, and the corresponding CNR level. For three imaging protocols, there was no mAs for which all observers scored the images 3 or more for any of the clinical applications. For another protocol, this was the case for 'implant planning'. For the two acceptability criteria (i.e. average score >2.5 or all observers scoring minimum 3), a wide range is seen for the minimal mAs value, mainly due to the high mAs for the CRANEX 3D high resolution protocol. For this protocol, amongst others, the lowest selectable mAs value was deemed acceptable for the 'average score' criterion and for the 'minimum score, sinus' criterion, indicating that it could be possible to reduce the exposure beyond the selectable range. A similar range is seen for the CNR values corresponding to these minimal mAs values. This is due to the disproportionally high CNR for the GALILEOS Comfort and SCANORA 3D large FOV, as demonstrated in the figures above.
Table 3: Intra-observer agreement, weighted kappa

<table>
<thead>
<tr>
<th>Observer</th>
<th>Observer 2</th>
<th>Observer 3</th>
<th>Observer 4</th>
<th>Observer 5</th>
<th>Observer 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer 1</td>
<td>0.677</td>
<td>0.594</td>
<td>0.415</td>
<td>0.347</td>
<td>0.450</td>
</tr>
<tr>
<td>Observer 2</td>
<td>0.585</td>
<td>0.393</td>
<td>0.336</td>
<td>0.394</td>
<td></td>
</tr>
<tr>
<td>Observer 3</td>
<td>0.409</td>
<td>0.363</td>
<td>0.519</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observer 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observer 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Contrast-to-noise ratio (CNR) versus tube current-time product (mAs)

Fig. 2: Contrast-to-noise ratio (CNR) versus tube current-time product (mAs)
Fig. 3: Axial slices at the level of the mental foramen, using the default mAs for each imaging protocol

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**Figure 4**: Axial slices at the level of the maxillary bone and sinus, using the default mAs for each imaging protocol
Figure 5: Relation between CNR and average score for all anatomical landmarks

Table 4: Difference between mandibular and maxillary scores. Positive values denote a higher score for mandible

<table>
<thead>
<tr>
<th>CBCT device and protocol</th>
<th>Cortical bone</th>
<th>Trabecular bone</th>
<th>PDL space</th>
<th>Lamina dura</th>
<th>Pulp canal</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Accuitomo 170, large FOV</td>
<td>0.27</td>
<td>-0.15</td>
<td>-0.01</td>
<td>0.07</td>
<td>0</td>
</tr>
<tr>
<td>3D Accuitomo 170, small FOV</td>
<td>0</td>
<td>0.04</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CRANEX 3D, low resolution</td>
<td>0.05</td>
<td>0.05</td>
<td>0</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>CRANEX 3D, high resolution</td>
<td>0.15</td>
<td>0.03</td>
<td>0.00</td>
<td>0</td>
<td>0.09</td>
</tr>
<tr>
<td>GALILEOS Comfort</td>
<td>0.45</td>
<td>0.18</td>
<td>0.08</td>
<td>0.08</td>
<td>0</td>
</tr>
<tr>
<td>SCANORA 3D, large FOV</td>
<td>0.31</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>SCANORA 3D, small FOV</td>
<td>0.09</td>
<td>0.10</td>
<td>0.03</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>0.19</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

PDL periodontal ligament

Table 4: Difference between mandibular and maxillary scores. Positive values denote a higher score for mandible
Figure 6 Relation between CNR and score for mental foramen and maxillary lamina dura

Fig. 6: Relation between CNR and score for mental foramen and maxillary lamina dura

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Figure 7: Relation between CNR and score for cortical bone, maxilla and mandible

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Figure 8: CNR versus observer scores for three clinical indications

**Fig. 8**: CNR versus observer scores for three clinical indications

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Table 5: Observer scores for anatomical parameters

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Table 6: Minimal mAs & CNR values for which average or minimum scores were above acceptable threshold

*Lowest selectable mAs value for this protocol
Conclusion

The relationship between technical image quality, measured as the CNR\textsubscript{AIR} corrected for voxel size, and the diagnostic image quality, measured as observer scores for anatomical landmarks and three clinical indications, was investigated. Although the mAs showed a fair correlation with the observer scores, the relation with the CNR was specific for each device. A multi-predictor model including both spatial resolution and contrast resolution may provide objective criteria for image quality which are reproducible between devices.

The current results allow for the definition of preliminary threshold values for CNR which can be used as a starting point for future investigations. For all CBCT devices, the lowest CNR values corresponding to an acceptable image quality for implant/root/sinus were 7.7 and 12.6/11.8/10.4, depending on the acceptability criterion.

This study indicates that it could be possible to reduce exposure levels below the manufacturer's recommended setting for certain patient groups. The definition of standardized objective image quality criteria for CBCT can guide all parties involved in CBCT imaging (i.e. users, manufacturers, medical physicist) to achieve minimal exposure levels in all circumstances.


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