Vol. 123 No. 1 January 2017

Accuracy of segmentation of tooth structures using 3 different CBCT machines

Eman Shaheen, MSc, PhD,[a,b] Wael Khalil, DDS, MSc,[a] Mostafa Ezeldeen, DDS, MSc,[a] Elke Van de Casteele, MSc, PhD,[a] Yi Sun, MSc, PhD,[a,b] Constantinus Politis, MD, DDS, MHA, MM, PhD,[a,b] and Reinhilde Jacobs, DDS, MSc, PhD, Dr hc[a,b,c]

Objective. The aim of this study was to evaluate the volumetric accuracy and reliability of cone beam computed tomography (CBCT)-based tooth segmentation using 4 different CBCT exposure protocols.
Methods. Two dry, intact adult human mandibles of unknown gender were scanned using 4 different CBCT exposure protocols (3 CBCT systems). The available mandibular premolars (3 per mandible) were segmented, resulting in a total of 24 segmented teeth. To assess the accuracy of the segmented teeth, volumetric and morphologic differences between the real anatomic teeth and the reconstructed images were evaluated both physically and using a high-resolution micro-computed tomography system.
Results. Results revealed a high accuracy of CBCT reconstructed images when comparing volumetric measures of CBCT-based segmented premolars to physical measurements of corresponding physical teeth. Volumetric differences were below 2%. Morphologic differences using the segmented model and the corresponding micro-computed tomography scans of the physical teeth indicated that when inaccuracies occurred, they were at the apical and coronal parts of the tooth.
Conclusion. Based on these results, CBCT can be used as a tool for segmentation and pretherapeutic planning procedures. (Oral Surg Oral Med Oral Pathol Oral Radiol 2017;123:123-128)

During the last decade, 3-dimensional (3-D) information has been used more frequently to assist in dentomaxillofacial diagnostics and surgical planning. However, the use of computed tomography (CT) in daily dental practice remains contested due to its high cost and high radiation exposure.[1] Alternatively, cone beam computed tomography (CBCT) has demonstrated utility, with higher spatial resolution, smaller exposure, and lower cost compared to CT, but it still lacks contrast accuracy[2] and evidence-based guidelines for a standardized protocol.[1,3]

Three-dimensional virtual models obtained from CBCT images could be valuable tools for diagnosis and treatment planning. They could have a major impact on clinical practice, especially when combined with 3-D printing technology. However, their accuracy and effectiveness must be assessed before these models can be adopted.[4] CBCT accuracy has been studied in order to establish dimensional verification, usually using osteologic landmarks on dry human skulls as reference points for measurement.[5-8]

In this context, the assessment should include all steps, starting from the accuracy of scanning to the segmentation procedure, the latter being a major step in creating accurate digital teeth to allow production of 3-D tooth models. However, to validate the accuracy of the resulting 3-D models, all steps must be taken into account. They include scanning, segmentation, and model fabrication, as previously validated and described by Shahbazian et al.[9,10]

The segmentation accuracy of CT has already been studied extensively.[11] In CT imaging, segmentation of objects or tissues is performed using thresholding based on prior knowledge of the density of the anatomic structure (Hounsfield units). Unfortunately, gray values cannot be used directly in a quantitative way in CBCT imaging.[2,12] In addition, low-contrast

Statement of Clinical Relevance

The use of cone beam computed tomography (CBCT)-based tooth segmentation and replica fabrication may help to enhance therapeutic outcomes. A tooth replica may provide optimal bone fit during tooth autotransplantation while reducing extra-alveolar time, thus preserving periodontal ligament and pulp vitality and reducing the risk of necrosis and resorption. Fabrication of the tooth replica is limited by the CBCT quality and the accuracy of the segmentation; therefore, studies exploring the influence of CBCT machines and protocols are highly relevant to this particular clinical application.

[a]OMFS IMPATH Research Group, Department of Imaging and Pathology, Faculty of Medicine, Katholieke Universiteit Leuven, Leuven, Belgium.
[b]Department of Oral and Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium.
[c]Department of Dental Medicine, Karolinska Institutet, Stockholm, Sweden.
Received for publication Apr 3, 2016; returned for revision Jul 28, 2016; accepted for publication Sep 15, 2016.

2212-4403/$ - see front matter
http://dx.doi.org/10.1016/j.oooo.2016.09.005

Table I. Specifications of the 4 cone beam computed tomography (CBCT) exposure protocols used for CBCT-based tooth segmentation

	Accuitomo 170 180°	*Accuitomo 170 360°*	*Scanora 3-D*	*ProMax Max*
Tube current (mA)	5	5	8	11
Gray scale (bit)	8	8	12	12
Potential (KV)	90	90	85	96
Scan time (s)	8 s/180°	17.5 s/360°	3.7 s/360°	15 s/210°
Reconstruction time (min)	5	5	1-2	3
Voxel size (mm)	0.16	0.16	0.2	0.15
Field of view (mm)	80 × 80	80 × 80	75 × 100	100 × 90
Detector type	Flat panel	Flat panel	Flat panel	Flat panel

segmentation in CBCT is hampered by higher image noise compared with CT.[13]

Tooth segmentation is more challenging than bone structure segmentation for several reasons, such as the number of teeth per jaw, the proximity of adjacent tooth structures, the difference in density within a tooth (enamel, dentin, cementum, and pulp chamber), and tooth development.[14] It is even more challenging to perform segmentation in CBCT images than in CT images. The studies that have considered the use of CBCT for tooth segmentation have been limited to only one system or protocol.[9,10]

The purpose of this study was to evaluate the volumetric and morphologic accuracy and reliability of CBCT-based tooth segmentation, based on different CBCT units and varying exposure parameter protocols.

MATERIALS AND METHODS

Study sample and collection

This study was carried out on 2 dry, intact adult human mandibles of unknown gender collected from the Department of Anatomy at KU Leuven. Ethical review board approval was obtained (ML9535/ML9248, ERB University Hospitals Leuven).

Image acquisition (cone beam computed tomography, micro-computed tomography)

The mandibles were placed on a plastic tray with copper filters of 0.5 mm in front of the X-ray beam source to simulate soft tissue and to reduce X-ray beam-hardening effects.[15] Both dry dentate mandibles were scanned using 3 different CBCT machines (Table I): Accuitomo 170 (Morita, Kyoto, Japan), Scanora 3-D (Soredex, Tuusula, Finland), and ProMax (Planmeca OY, Helsinki, Finland). For the Accuitomo 170, 2 different scanning protocols were used, half and full rotation. In total, 8 mandible scans were obtained. The 3 available mandibular premolars were selected from each of the 2 mandibles for further tooth segmentation, resulting in a total of 24 segmented teeth. All data sets were exported using the Digital Imaging and Communications in Medicine (DICOM) file format. An example of an extracted premolar (tooth #21) from one of the dry mandibles is shown in Figure 1, with the corresponding segmented output.

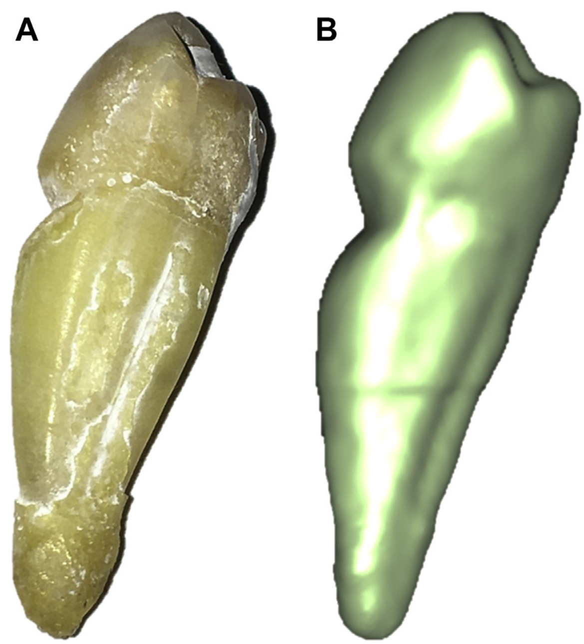

Fig. 1. **A,** The physical tooth (#21) as it was extracted from the dry mandible. **B,** The segmented model of the same tooth.

Data processing

All premolars were segmented from the DICOM images using the SimPlant Pro 3-D planning software (version 12.01, Dentsply Implants, Mölndal, Sweden) following a predefined protocol.[3] The segmentation protocol has been previously validated[9] and explained in more detail.[16]

Accuracy assessment

To assess segmentation accuracy, dimensional differences between the real anatomic teeth (volume determined using the Archimedes principle, as described by Khalil et al.[16]) and the segmented teeth were evaluated.

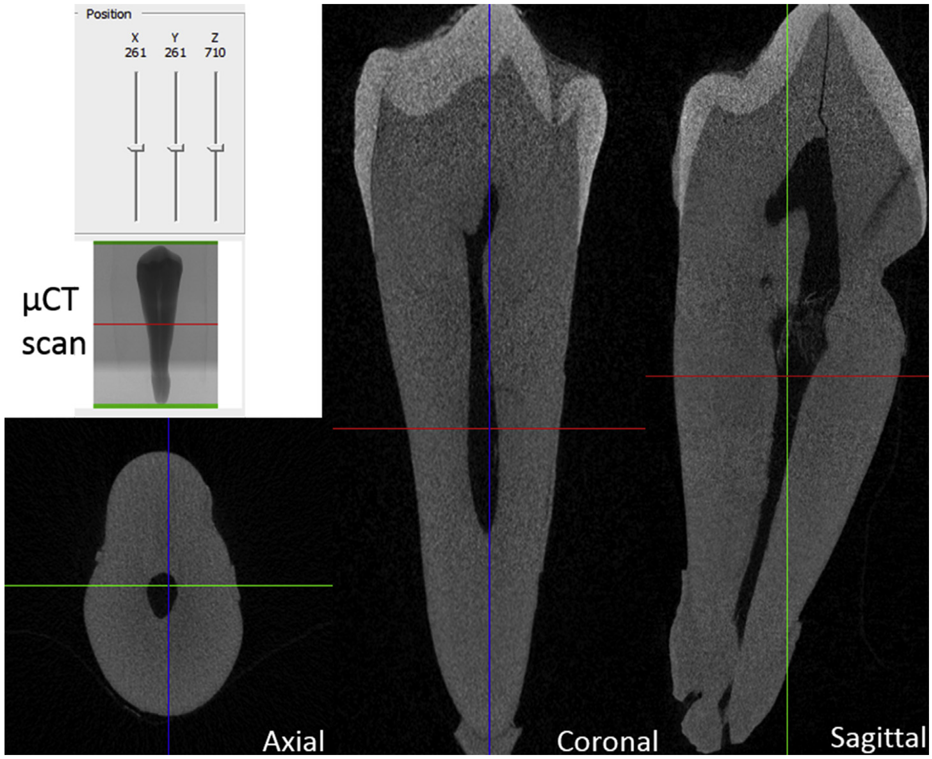

Fig. 2. Example of a premolar scanned with the microcomputed tomography (µCT) system and the reconstructed volume in 3 orthogonal views (axial, coronal, and sagittal).

In a second step, a micro-CT (µCT) system was used for reference images because of its high resolution. Volumetric comparisons were made between the segmented teeth from the different CBCT protocols and the corresponding segmentations from the µCT images.

Each tooth was extracted from the dry mandible and scanned separately in the SkyScan 1172 µCT scanner (Bruker micro-CT, Kontich, Belgium). In a full rotation setting, with a voxel of size 17.8 µm, the source was set at 100 kV/100 µA, and an aluminum-copper filter was used to reduce the beam-hardening effect. To increase the signal-to-noise ratio, the frame averaging was set at 6 frames per rotation step. Projection images were obtained over 180° with a rotation step of 0.7°. The exposure time was 316 milliseconds, leading to a scan time of 12 minutes per scan. After acquisition, reconstruction was done using NRecon software (Bruker micro-CT). Reconstruction parameters were as follows: Gaussian smoothing of 1, ring artifact correction of 7, and beam-hardening correction of 30%. After reconstruction, the teeth were segmented from the images to obtain 3-D surface-rendered models, and the corresponding volumes were calculated using CTAnalyser (Bruker micro-CT). Figure 2 shows an example of a premolar scanned with the µCT system and the reconstructed volume in 3 orthogonal views (axial, coronal, and sagittal).

The 3-D models of the segmented teeth obtained from the CBCT and µCT scans were registered using 3-matic software (version 9.0, Materialise NV, Leuven, Belgium). Morphologic errors and volumetric changes between the CBCT and µCT models were measured via a point-based signed part comparison method, resulting in a color-coded map. This map expresses the distribution of the surface distance (Euclidean distance) between each point on the surface of the segmented tooth from CBCT and its corresponding point from µCT. Distances greater than 0.25 mm are represented in red, differences of approximately zero are represented in green, and intermediate distances are represented in orange. An example is shown in Figure 3.

Statistical analysis

All data were analyzed with the IBM Statistical Package for Social Sciences (SPSS, version 21.0, IBM Corporation, Armonk, NY, USA). A comparison between the volume measurements of the physical teeth and the CBCT data sets was performed using repeated analysis of variance; the significance level was set at $P \leq .05$. Pearson correlation was performed to examine the potential linear relationships. The degree of agreement between the volume measurements was compared using the Bland and Altman method.[17]

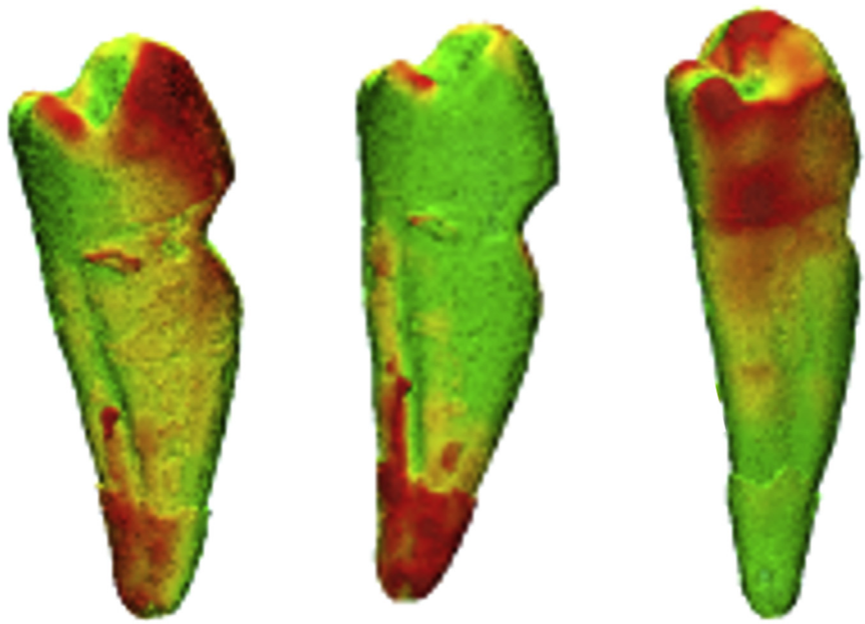

Fig. 3. Color-coded visualization in part comparison analysis showing localization of inaccuracies. Red represents large deviations (distances >0.25 mm), green represents small deviations (distances around 0 mm), and orange represents intermediate deviations between green and red.

Table II. Pearson coefficients (R) of microcomputed tomography (µCT) volume measurements, cone beam computed tomography (CBCT) volume measurements, and physical measurements determined using the Archimedes principle

	CBCT versus µCT	
	R	P *value*
Accuitomo 170 180° rotation (virtual 3-D model)	0.91	.013*
Accuitomo 170 360° rotation (virtual 3-D model)	0.93	.007†
Promax Max (virtual 3-D model)	0.92	.008†
Scanora 3-D (virtual 3-D model)	0.93	.008†
Physical	0.91	.012*

*Significance at $P < .05$.
†Significance at $P < .01$.

Table III. Mean absolute difference in percentage of cone beam computed tomography (CBCT) volume measurements and physical measurements determined using the Archimedes principle and microcomputed tomography (µCT)

	Mean absolute difference in percentage
Physical volume and Accuitomo 170 (180° rotation)	1.9%
Physical volume and Accuitomo 170 (360° rotation)	1.6%
Physical volume and Promax Max	2.1%
Physical volume and Scanora 3-D	0.9%
µCT and Accuitomo 170 180° rotation	3.6%
µCT and Accuitomo 170 360° rotation	3.2%
µCT and Promax Max	3.8%
µCT and Scanora 3-D	2.4%
µCT and Physical	1.6%

RESULTS

The volume measurements of the µCT revealed a strong positive correlation with those of the 4 CBCT protocols and with the physical measurements determined using the Archimedes principle ($r > 0.90$) when evaluated using the Pearson correlation (Table II).

The mean absolute difference in percentage between physical measurements determined using the Archimedes principle and CBCT volume measurements was calculated using the Bland-Altman method and was found to be 1.9% with Accuitomo 170 180° rotation, 1.6% with Accuitomo 170 360° rotation, 2.1% with Promax Max, and 0.9% with Scanora 3-D (Table III).

The mean absolute difference between µCT and CBCT volume measurements was found to be 3.6% with Accuitomo 170 180° rotation, 3.2% with Accuitomo 170 360° rotation, 3.8% with Promax Max, and 2.4% with Scanora 3-D (Table III).

Moreover, the mean absolute difference in percentage between µCT volume measurements and physical

Table IV. Comparison of microcomputed tomography (μCT) volume measurements, cone beam computed tomography (CBCT) volume measurements, and physical measurements using analysis of variance (ANOVA) with repeated measures

Comparisons	P *value*
μCT and CBCT (Accuitomo 170 180°, Accuitomo 170 360°, Promax, Scanora)	.146
μCT and Archimedes' volumetry	.489

Note. Level of significance set at $P < .05$.

measurements determined using the Archimedes principle of the teeth was 1.6% (Table III).

The results of repeated analysis of variance revealed no statistically significant differences between μCT and CBCT volume measurements ($P = .146$). Furthermore, no statistically significant difference was found between μCT and physical volume measurements ($P = .489$) (Table IV).

Morphologic analysis showed that 95% of the differences between surfaces ranged from −3.3 to +1.5 mm, with a mean of −0.5 mm and a standard deviation of 0.8 mm. According to the color-coded map, higher deviations (red areas) were found in the apical region (18 models out of 24) and the coronal part (14 out of 24); only a few models showed inaccuracies in the root part (Figure 3).

DISCUSSION

When looking at the future of 3-D printed medical tools and replicas as a support for clinical diagnosis, planning, and treatment, it is of utmost importance to assess the accuracy of the virtual 3-D model obtained after segmentation. Since the CBCT data sets can be obtained from different scanners or scanning protocols, the present study assessed the accuracy and robustness of the obtained virtual 3-D models.

Volumetric measurements were made using the Archimedes principle, given its simplicity, consistency, and accuracy in measuring the volume of a given object with homogenous density.[18] The mean volumetric differences for the Archimedes method and CBCT measurements varied in our study from 0.9% to 2.1%, which is consistent with the findings of studies conducted in similar settings.[19-22] Compared with μCT, the volume measurements and physical measurements were overestimated and varied from 1.9% to 3.6%. As previously calculated by Star et al.,[23] the mean volume of the pulp is about 2% to 3% of the volume of the tooth. Therefore, the differences could be explained by the fact that the root canal was segmented in the μCT images but not in the CBCT images, due to the difficulty of segmentation. Furthermore, the lower resolution of CBCT (voxel size range 0.15-0.2 mm) compared to μCT (voxel size 0.0178 mm) may have contributed to this error. For correlational accuracy, it was shown that high correlation coefficients were found between the segmented volumes and the original volumes in both applications (Archimedes and μCT), which is also consistent with other studies.[24]

CBCT imaging quality is related to the machine settings, patient positioning, volume reconstruction, and DICOM export. These factors could affect the accuracy assessment. In the present study, data sets were collected from 3 different CBCT systems, with fixed mandibles instead of patients who may move. This factor was not included in this study and thus is considered a limitation that should be tested in future work. Another possible factor that was not included in this study was the effect of artifacts, such as metal artifacts.[25] The presence of artifacts in the scan, whether in the neighborhood of the tooth of interest or not, would affect the gray values and thus the quality of the segmentation, which is based on thresholding.

The voxel sizes of the CBCT scan protocols used to scan teeth with the purpose of segmentation or diagnostic evaluation fell approximately within the range covered in this study (0.15-0.2 mm). Even though no statistically significant difference was found among all scanning protocols and the reference (whether μCT or physical) for the covered range, larger voxel sizes were not considered based on the findings of Maret et al.[26] In their study, underestimations were found for scans with a voxel size of 0.3 mm.

CONCLUSION

In the present study, results reveal that all tested CBCT protocols provided high accuracy for tooth segmentation compared with anatomic tooth morphology. Therefore, CBCT-segmented teeth can be recommended as a tool for diagnostic and pretherapeutic planning procedures.

REFERENCES

1. Liang X, Jacobs R, Hassan B, et al. A comparative evaluation of cone beam computed tomography (CBCT) and multi-slice CT (MSCT), part I. On subjective image quality. *Eur J Radiol.* 2010;75:265-269.
2. Pauwels R, Jacobs R, Singer SR, Mupparapu M. CBCT-based bone quality assessment: are Hounsfield units applicable? *Dentomaxillofac Radiol.* 2015;44:20140238.
3. Loubele M, Maes F, Schutyser F, Marchal G, Jacobs R, Suetens P. Assessment of bone segmentation quality of cone-beam CT versus multislice spiral CT: a pilot study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2006;102:225-234.
4. Al-Rawi B, Hassan B, Vandenberge B, Jacobs R. Accuracy assessment of three-dimensional surface reconstructions of teeth from cone beam computed tomography scans. *J Oral Rehabil.* 2010;37:352-358.

5. Lagravre MO, Carey J, Toogood RW, Major PW. Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images. *Am J Orthod Dentofacial Orthop*. 2008;134:112-116.
6. Loubele M, Van Assche N, Carpentier K, et al. Comparative localized linear accuracy of small-field cone-beam CT and multislice CT for alveolar bone measurements. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2008;105:512-518.
7. Periago DR, Scarfe WC, Moshiri M, Scheetz JP, Silveira AM, Farman AG. Linear accuracy and reliability of cone beam CT derived 3-dimensional images constructed using an orthodontic volumetric rendering program. *Angle Orthod*. 2008;78:387-395.
8. Hassan B, van der Stelt P, Sanderink G. Accuracy of three-dimensional measurements obtained from cone beam computed tomography surface-rendered images for cephalometric analysis: influence of patient scanning position. *Eur J Orthod*. 2009;31:129-134.
9. Shahbazian M, Jacobs R, Wyatt J, et al. Accuracy and surgical feasibility of a CBCT-based stereolithographic surgical guide aiding autotransplantation of teeth: in vitro validation. *J Oral Rehab*. 2010;37:854-859.
10. Shahbazian M, Jacobs R, Wyatt J, et al. Validation of the cone beam computed tomography−based stereolithographic surgical guide aiding autotransplantation of teeth: clinical case-control study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2013;115:667-675.
11. Aamodt A, Kvistad KA, Andersen E, et al. Determination of Hounsfield value for CT-based design of custom femoral stems. *J Bone Joint Surg Br*. 1999;81:143-147.
12. Pauwels R, Nackaerts O, Bellaiche N, et al. Variability of dental cone beam CT grey values for density estimations. *Br J Radiol*. 2013;86:20120135.
13. Hiew LT, Ong SH, Foong KWC. Tooth Segmentation From Cone-Beam CT using graph cut. Proceedings of the Second APSIPA Annual Summit and Conference. December 14-17, 2010; Biopolis, Singapore.
14. Hui G, Oksam C. Individual tooth segmentation from CT images using level set method with shape and intensity prior. *Pattern Recognition*. 2010;43:2406-2417.
15. Suomalainen A, Vehmas T, Kortesniemi M, Robinson S, Peltola J. Accuracy of linear measurements using dental cone beam and conventional multislice computed tomography. *Dentomaxillofac Radiol*. 2008;37:10-17.
16. Khalil W, EzEldeen M, Van De Casteele E, et al. Validation of cone beam computed tomography−based tooth printing using different three-dimensional printing technologies. *Oral Surg Oral Med Oral Pathol Oral Radiol Oral Endod*. 2016;121:307-315.
17. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;1:307-310.
18. Hughes SW. Archimedes revisited: a faster, better and cheaper method of accurately measuring the volume of small objects. *Physics Education*. 2005;40:468-474.
19. Agbaje JO, Jacobs R, Maes F, Michiels K, van Steenberghe D. Volumetric analysis of extraction sockets using cone beam computed tomography: a pilot study on ex vivo jaw bone. *J Clin Periodont*. 2007;34:985-990.
20. EzEldeen M, Van Gorp G, Van Dessel J, Vandermeulen D, Jacobs R. CBCT-based bone quality assessment: are Hounsfield units applicable? *J Endod*. 2015;41:317-324.
21. Liu Y, Olszewski R, Alexandroni ES, Enciso R, Xu T, Mah JK. The validity of in vivo tooth volume determinations from cone-beam computed tomography. *Angle Orthod*. 2010;80:160-166.
22. Pinsky HM, Dyda S, Pinsky RW, Misch KA, Sarment DP. Accuracy of three-dimensional measurements using cone-beam CT. *Dentomaxillofac Radiol*. 2006;35:410-416.
23. Kamburoglu K, Kolsuz E, Kurt H, Kiliç C, Özen T, Paksoy CS. Accuracy of CBCT measurements of a human skull. *J Digit Imaging*. 2011;24:787-793.
24. Star H, Thevissen P, Jacobs R, Fieuws S, Solheim T, Willems G. Human dental age estimation by calculation of pulp-tooth volume ratios yielded on clinically acquired cone beam computed tomography images of monoradicular teeth. *J Forensic S*. 2011;56:S77-S86.
25. Vasconcelos KF, Nicolielo LF, Nascimento MC, et al. Artefact expression associated with several cone-beam computed tomographic machines when imaging root filled teeth. *Int Endod J*. 2014;10:994-1000.
26. Maret D, Telmon N, Peters OA, et al. Effect of voxel size on the accuracy of 3 D reconstructions with cone beam CT. *Dentomaxillofac Radiol*. 2012;41:649-655.

Reprint requests:

Reinhilde Jacobs
Omfs Impath research group
Department of Imaging and Pathology
Faculty of Medicine
Katholieke Universiteit Leuven
Kapucijnenvoer 33
3000 Leuven
Belgium
reinhilde.jacobs@med.kuleuven.be