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Validation and comparison of volume measurements using 1 multidetector computed tomography and 5 cone-beam computed tomography protocols: An in vitro study

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ABSTRACT

Purpose: The purpose of this study was to compare volume measurements obtained using 2 image software packages on Digital Imaging and Communications in Medicine (DICOM) images acquired from 1 multidetector computed tomography and 5 cone-beam computed tomography devices, using different protocols for physical volume measurements.

Materials and Methods: Four pieces of bovine leg were prepared. Marrow was removed from 3 pieces, leaving cortical bone exposed. The resulting space of 1 piece was filled with water, another was filled with propylene glycol, and the third was left unfilled. The marrow in the fourth sample was left fully intact. Volume measurements were obtained after importing DICOM images into the Dolphin Imaging 11.95 and ITK-SNAP software programs. Data were analyzed using 3-way analysis of variance with a generalized linear model to determine the effects of voxel size, software, and content on percentage mean volume differences between tomographic protocols. A significance level of 0.05 was used.

Results: The intraclass correlation coefficients for intraobserver and interobserver reliability were, respectively, 0.915 and 0.764 for the Dolphin software and 0.894 and 0.766 for the ITK-SNAP software. Three sources of statistically significant variation were identified: the interaction between software and content ($P = 0.001$), the main effect of content ($P = 0.014$), and the main effect of software ($P = 0.001$). Voxel size was not associated with statistically significant differences in volume measurements.

Conclusion: Both content and software influenced the accuracy of volume measurements, especially when the content had gray values similar to those of the adjacent tissues. ***(Imaging Sci Dent 2022; 52: 399-408)***

KEY WORDS: Dimensional Measurement Accuracy; Multidetector Computed Tomography; Cone-Beam Computed Tomography; Software

Introduction

Computed tomography (CT) images are being increasingly utilized, revealing new diagnostic possibilities.[1-3] Despite its proven effectiveness, multidetector computed tomography (MDCT) is not widely used in dental practice because of its high cost, availability limited to large medical radiological centers, and high levels of radiation exposure.[4]

Cone-beam computed tomography (CBCT) was developed to overcome the limitations of MDCT and respond to the increasing demand for better images of the dentomaxillofacial complex.[5,6] CBCT is a 3-dimensional technique with low radiation dosage that enables visualization of bone structures in the head and neck.[7] In a subjective comparison of image quality, images acquired with CBCT were found to be significantly superior to MDCT images. In addition, the skin radiation dose associated with CBCT was shown to be extremely low. This information sup-

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ports the efficacy of CBCT for the diagnosis and examination of hard tissues in the maxillofacial region.[8]

One important advantage of CT images, whether obtained using MDCT or CBCT equipment, is the possibility of interaction with stored data. Images are usually stored in the Digital Imaging and Communications in Medicine (DICOM) format. Using specific software, these digital files can be converted into multiplanar images (axial, coronal, and sagittal). Moreover, available tools can be used to conduct measurements and generate 3-dimensional digital images.

The assessment of volume using CT images has become increasingly common. Airway volumes have been measured to compare preoperative and postoperative clinical situations,[9] associate variations with anatomical changes,[10,11] and examine cases of cleft palate.[12,13] Notable pathology-related measurement applications include the volume assessment of periapical lesions and the follow-up assessment of bone healing after treatment.[14,15] CBCT images have also been used to evaluate cleft palates and to predict the bone graft volumes needed to correct them.[16,17]

Perhaps the greatest limitation of clinical studies on this topic is the absence of a gold standard.[18,19] Some tests have been conducted to validate volume measurements in *in vitro* CBCT studies simulating bone defects,[20,21] but only 2 studies were found in which volumes of materials with different densities were compared using a physical gold standard. In 1 study, the volumes measured on MDCT images of simulated oral clefts submerged in water, with and without wax, were compared.[22] In the other study, also focused on simulated oral clefts, pre- and post-graft volume measurements derived from CBCT images were compared.[23] Neither study reported statistically significant differences between volume measurements.

Under clinical conditions, structures or lesions are filled or coated with soft tissues, which may interfere with the acquisition of tomographic images or with measurements made using these images. Therefore, sufficient justification exists for a study to compare and verify the accuracy of volume measurements on CT images simulating diverse clinical and pathological situations. The aim of this *in vitro* study was to verify the accuracy of volume measurements obtained using 2 image software programs and the included volume measurement tools on DICOM images obtained with 1 MDCT and 5 CBCT devices. Multiple protocols and contents were used, and the results were compared to physical volume measurements. Measurement reliability was also assessed.

Materials and Methods

This *in vitro* experimental study was approved by the Research Ethics Committee on August 17, 2015. It was conducted in the Oral Radiology Department of the Dental School at the Federal University of Rio Grande do Sul in Porto Alegre, RS, Brazil.

Four pieces of bovine leg comprising bone, muscle, and marrow were obtained in approximately 20-mm-thick slices. Marrow was removed from 3 pieces, leaving internal cortical bone exposed. To simulate different clinical and pathological situations (such as cysts, pseudocysts, traumatic bone cysts, bone defects, or unfilled pathologic cavities), in 1 sample, the hollow space from which marrow had been removed was filled with water. In another, it was filled with propylene glycol (simulating a blood-like density of 1.04 g/cm^3), and the space in the third sample was left unfilled. The marrow in the fourth sample was left fully intact. Each sample was placed in an acrylic recipient to facilitate filling with water and propylene glycol. The bovine muscle was used as a soft tissue simulator to attenuate the x-ray beam (Fig. 1).

Tomographic images were obtained with an MDCT device using a skull protocol and reconstructed with the bone and soft tissue kernels. Images were also acquired with 5 CBCT devices using routine clinical protocols (Table 1). Specimens were placed so that the X-ray beam could pass perpendicularly through muscle, bone, and marrow (Fig. 1). Images were exported as DICOM files.

Volume measurement

Physical volume was calculated using the Archimedes principle. An impression of each of the 4 marrow regions

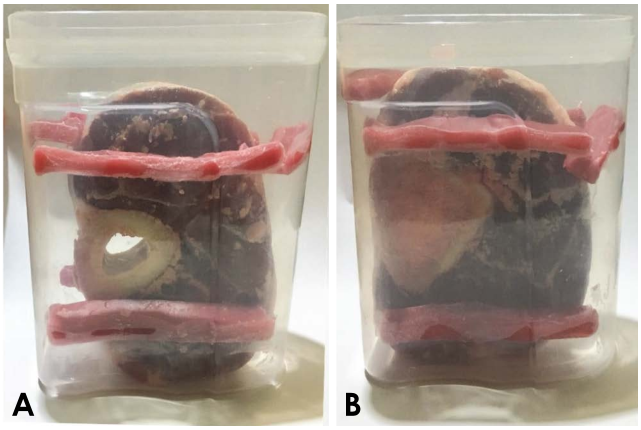

Fig. 1. Specimen positioning for tomographic acquisition. A. Specimen without marrow. B. Specimen with marrow preserved.

Table 1. Multidetector computed tomography (MDCT) AND cone-beam computed tomography (CBCT) protocols and mean volumes measured using each protocol and software

Equipment	Peak kilovoltage (kVp)	Current (mA)	Voxel size (mm)	Unfilled specimen (mm^3)	Water-filled specimen (mm^3)	Propylene glycol-filled specimen (mm^3)	Intact marrow specimen (mm^3)
Gold standard (impression)	–	–	–	8326.6	6441.3	17208.3	18620.6
i-CAT Next Generation (CBCT)							
Dolphin	120	5	0.2	8315.3	6212.3	17325.3	18970.0
			0.3	8306.3	6185.3	17131.6	19113.0
ITK-SNAP	120	5	0.2	8356.3	6175.0	17242.4	17657.5
			0.3	8420.0	6071.0	17026.5	17549.8
Orthopantomograph® OP300 (CBCT)							
Dolphin	90	6.3	0.2	8283.6	6421.6	17444.3	19211.3
		12.5	0.3	8355.0	6439.3	17473.3	19213.3
		5	0.33	8349.0	6457.0	17379.3	19306.3
ITK-SNAP	90	6.3	0.2	8396.0	6427.0	17407.7	17490.1
		12.5	0.3	8408.3	6509.3	17307.3	17672.7
		5	0.33	8276.3	6478.0	17121.4	17453.5
Pax-i3D (CBCT)							
Dolphin	85	5.2	0.12	8204.0	6349.3	17377.0	19620.0
			0.2	8243.6	6325.0	17252.3	19173.0
			0.3	8204.0	6298.6	17212.3	19186.6
ITK-SNAP	85	5.2	0.12	8251.6	6187.0	16932.7	17518.9
			0.2	8094.6	6147.6	16590.8	17539.5
			0.3	8251.6	6238.0	16968.2	17387.4
Kodak 9000 3D (CBCT)							
Dolphin	74	10	0.2	8121.3	5954.6	16655.3	18463.6
ITK-SNAP	74	10	0.2	8194.6	5987.3	16323.8	17250.1
Kodak 9500 (CBCT)							
Dolphin	85	12	0.2	8348.6	6434.6	17332.0	19579.6
			0.3	8496.0	6392.0	17547.3	19907.0
ITK-SNAP	85	12	0.2	8378.0	6326.6	17212.7	17740.7
			0.3	8423.6	6486.6	16900.7	17659.5
GE BrightSpeed 16C (MDCT)							
Dolphin	120	8 to 200 mA according to sample density	0.625	8728.6	6550.6	17505.6	18804.0
ITK-SNAP	120	8 to 200 mA according to sample density	0.625	8409.6	6298.3	17027.6	17496.1

CBCT: cone-beam computed tomography, MDCT: multidetector computed tomography.

was taken using polyvinylsiloxane, addition-type, surface-activated silicone elastomer (PRESIDENT The Original® Putty Soft; Coltene, Altstätten, Switzerland) manipulated according to the manufacturer's instructions (Fig. 2). Excess impression material was removed. A transparent glass graduated cylindrical measuring flask was used on which the 10-mL mark corresponded to a height of 8 mm. The cylinder was filled with water, and the initial water level was marked. Each impression was individually fully immersed in the cylinder. In accordance with the water displacement technique, the new water level was again marked. The difference between the heights represented the water displaced by the impression. The distance, in millimeters, between the 2 marks was obtained with a digital caliper. This value was employed in the following formula:

$$\text{Volume (mL)} = \text{distance of water displaced (mm)} \times 10\ \text{mL} / 8\ \text{mm}$$

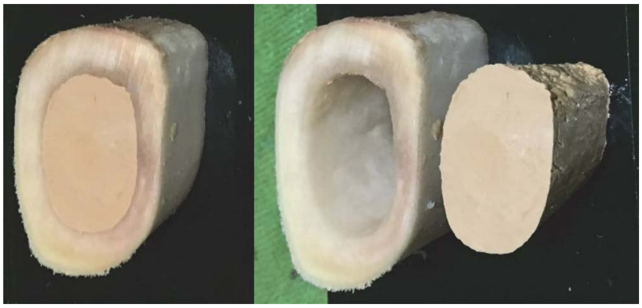

Fig. 2. Impression of the marrow region to determine the gold-standard volume.

and used to calculate the impression volume. The process was repeated 3 times for each impression, and the mean of the 3 measurements was calculated, defined as the physical volume, and used as the gold-standard measurement.

Volume measurements were obtained by importing all DICOM images into 2 image software programs: Dolphin Imaging 11.95 (Dolphin Imaging and Management Solutions, Chatsworth, CA, USA) and ITK-SNAP version 3.6.0 (http://itksnap.org).[24] Images were viewed on a 22-inch flat-screen monitor (Flatron E2250, 1920 × 1080 dpi;

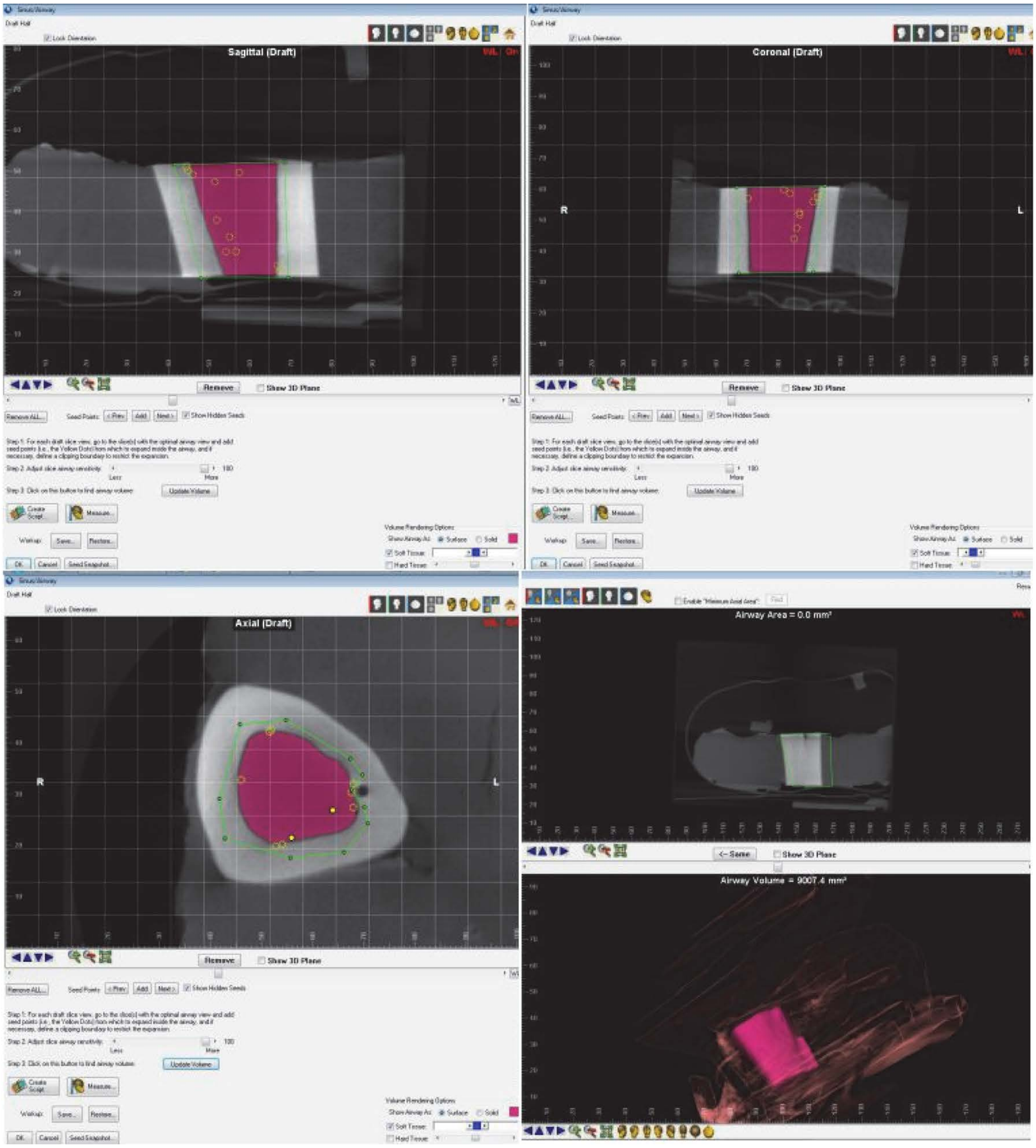

Fig. 3. Dolphin Imaging software: sagittal, coronal, and axial views and reconstructed 3-dimensional volume.

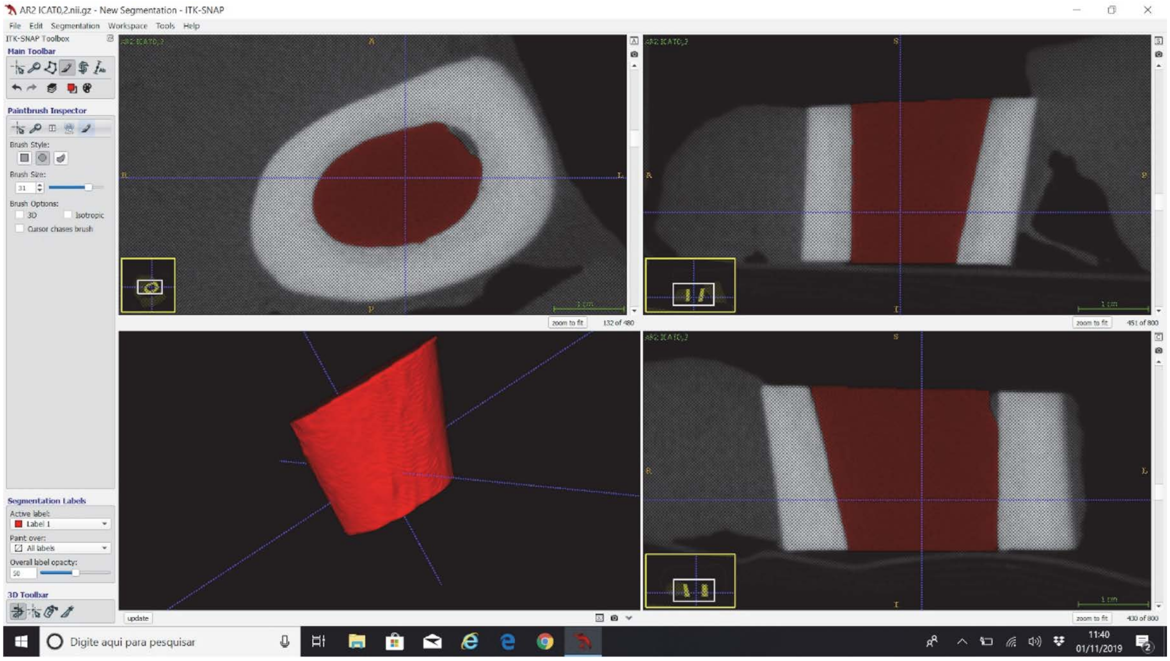

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Fig. 4. ITK-SNAP software: sagital, coronal, and axial views and reconstructed 3-dimensional volume.

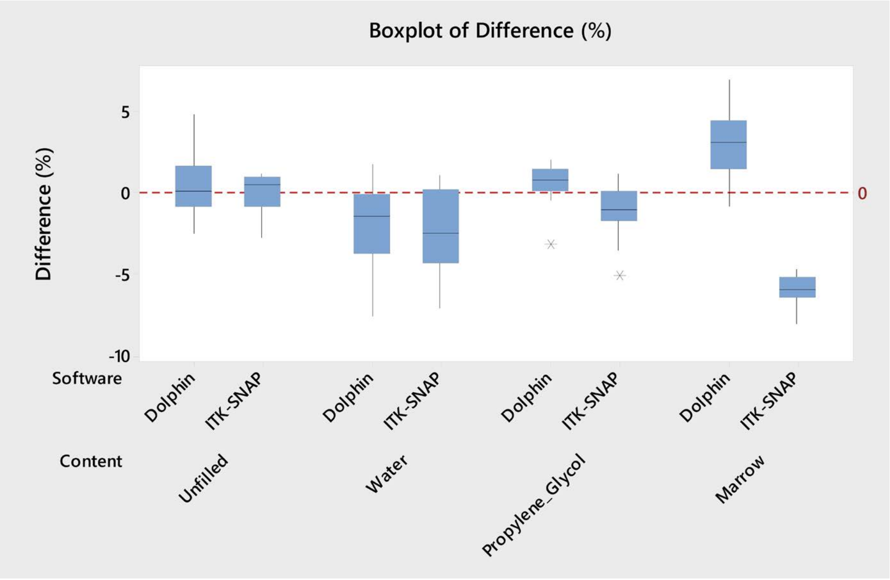

Fig. 5. Boxplot of differences (%) based on content and software.

LG, Taubaté, SP, Brazil).

One trained and calibrated examiner (JACT) measured volumes in all 4 sample images (water-filled, propylene glycol-filled, marrow-filled, and unfilled) acquired with the CT and CBCT devices using all protocols. All measurements were repeated 3 times, with a minimum interval between measurements of 2 weeks. Each volume was obtained by calculating the mean of the 3 measurements (Table 1).

The sinus/airway tool available in the Dolphin Imaging program was used to define and calculate the volumes. The sensitivity of the tool was carefully determined for each image, and the operator manually defined the extent of the marrow region by adjusting the sagittal, coronal, and axial slices, as shown in Figure 3. Thereafter, volumetric measurements were automatically determined, in

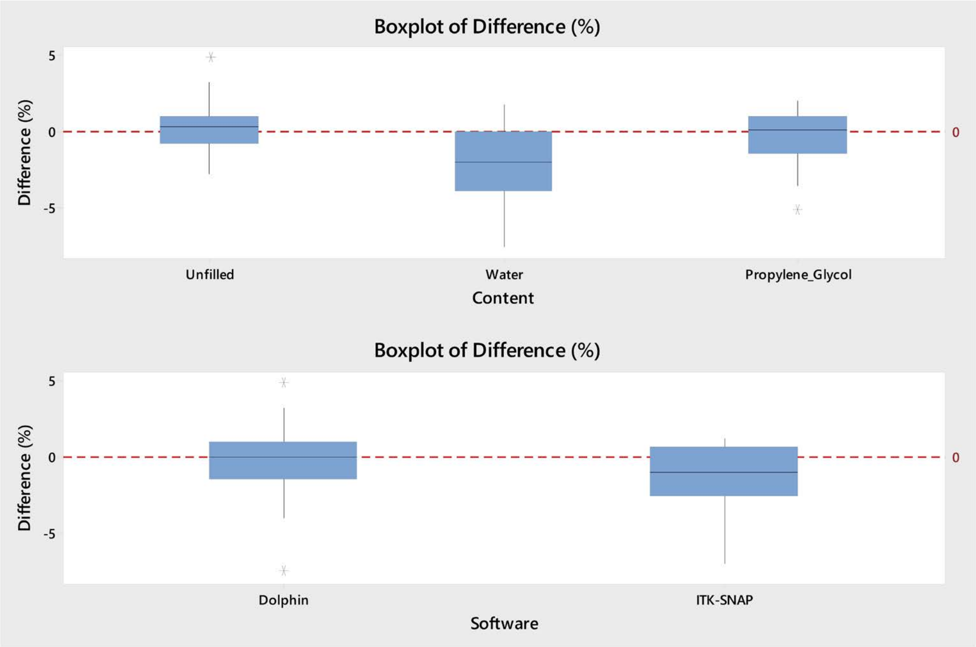

Fig. 6. Boxplot of differences (%) based on content and software and excluding the data for specimens with intact marrow.

mm^3, by the software.

In the ITK-SNAP software, images were also semi-automatically segmented by specifying the region of interest, manually setting the parameters and initial seeds, and supervising the active contour evolution (Fig. 4).[25] As with the Dolphin software, volumetric measurements were obtained in mm^3.

Reliability

To calibrate the evaluator (JACT), 1 examiner trained in Dolphin (MBV) and 1 in ITK-SNAP (PFTS) software conducted volume measurements in a pilot sample. Measurements were repeated after a 2-week interval. Reliability was assessed by calculating intraobserver and interobserver error values using intraclass correlation coefficients in SPSS version 15.0 for Windows (SPSS Inc., Chicago, IL, USA).

Validation of volumetric methods and statistical analysis

To validate the volumetric measurements, the mean values obtained for each sample in both software programs and with all protocols for the 5 CBCT devices and the MDCT device were put into Microsoft Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) and compared with the gold-standard values. Data were analyzed using 3-way analysis of variance (ANOVA) with a significance level of 0.05.

Results

Reliability

The intraobserver and interobserver reliability values calculated using intraclass correlation coefficients were, respectively, 0.915 and 0.764 for the Dolphin software and 0.894 and 0.766 for the ITK-SNAP software.

Gold standard

Physical volumes, obtained using the Archimedes principle, were defined as the gold standard and calculated by taking the mean of 3 measurements. These mean values were 8326.6 mm^3 for the unfilled specimen, 6441.3 mm^3 for the water-filled specimen, 17208.3 mm^3 for the specimen filled with propylene glycol, and 18620.6 mm^3 for the specimen with intact marrow.

Validation of volumetric methods and statistical analysis

Three-way ANOVA was conducted using a generalized linear model to determine the effects of voxel size, software, and content on the mean percentage volume difference between tomographic protocols. Three sources of statistically significant variation were found: the interaction between software and content ($F [3, 61]=18.62$, $P=0.001$), the main effect of content ($F [3, 61]=3.86$, $P=0.014$), and the main effect of software ($F [1, 61]=52.07$, $P=0.001$). Voxel size was not associated with sta-

Table 2. Three-way analysis of variance using a generalized linear model to analyze the effects of voxel size, software, and content on mean volume percentage difference concerning tomographic protocols

Source	DF	Adj SS	Adj MS	F	*P*
Content	3	41.6	13.8	3.86	<0.05
Voxel size	4	23.8	5.9	1.66	0.172
Software	1	187.3	187.3	52.07	<0.05
Content - voxel size	12	57.4	4.7	1.33	0.225
Content - software	3	200.9	66.9	18.62	<0.05
Voxel size - software	4	15.3	3.8	1.07	0.381
Content - voxel size - software	12	20.2	1.6	0.47	0.926
Error	61	219.4	3.5		
Total	100	966.5			

DF: degrees of freedom, Adj: adjusted.

tistically significant differences in volume measurements (Table 2).

Further analyzing the significant results for content and software, the boxplot in Figure 5 illustrates a significantly greater difference between the software programs for marrow than for the other materials. For marrow, the interaction between content and software was significant. Regardless of content or software, all measurements varied less than 10% from the gold standard. Additionally, considering only the unfilled specimens and those filled with water or propylene glycol, most measurements varied less than 5%.

The 3-way ANOVA was conducted again without the results for the specimens with intact marrow, and the interaction between content and software was no longer significant. Figure 6 illustrates an analysis without the data for the marrow-intact specimens, with the differences (%) for content and software evaluated individually.

Regarding content, the software measurements of the unfilled specimens and the specimens filled with propylene glycol were relatively close to the gold-standard measurements, while the software measurements of the water-filled specimens tended to be underestimates. Of the programs, Dolphin was more accurate, while ITK-SNAP tended to underestimate volumes.

Discussion

A valuable aspect of *in vitro* studies is the potential for simulating different clinical conditions with a single assessment. However, achieving this can sometimes be very complex. In this study, for example, the samples had different sizes and shapes for each type of content, so evaluating averages was difficult given the potential for underestimation or overestimation due to possible distortion of values. Therefore, measurement accuracy was estimated by comparing the mean differences between the software measurements of each type of content analyzed and the gold-standard measurements.

In a clinical study to validate the volumetric analysis of teeth with orthodontic indications for extraction, Liu et al.[26] reported that CBCT measurements seemed to be accurate. However, the researchers did not state this categorically due to the absence of a criterion for accuracy of volumetric determinations. Indeed, they observed that no consensus exists regarding the acceptable range for a measurement to be considered accurate, and most studies do not explain the parameters adopted. In a study of mandibular measurements, Whyms et al.[27] assessed the accuracy of digital volume measurements relative to a gold standard by calculating the average absolute relative error. In that study, an absolute relative error of 0.05, which equates to an average difference of less than 5% between anatomical and digital measurements, was considered acceptably accurate. However, it is not yet known what influence this variation might have in clinical situations. Is 5% really a good parameter of acceptability? Should this parameter be lower, or could it even be higher? The answer may depend on absolute structure volume. Based on this 5% threshold, the present study yielded accurate measurements for all unfilled specimen trials, regardless of software, equipment, or protocol.

In this area of research, few studies have been conducted to compare the volumes of different contents. In an *in vitro* study using skulls submerged in water, multislice CT-based volume measurements of simulated oral clefts filled and unfilled with wax were compared to a physical gold standard. The average volume measurement of the samples without wax was closer to the average gold-standard volume than was the measurement for the samples with wax. However, all 3 volumes were statistically equivalent, with 99% reliability.[22] In another *in vitro* oral cleft study, Amirlak et al.[23] used CBCT images to compare volume measurements of simulated defects with simulated bone grafts to a physical gold standard, and they also observed no statistically significant differences between volume measurements. However, that study did reveal that simulated bone graft volume measurements tended to underestimate the volume. In the present study, a tendency was also observed for software measurements to underestimate the marrow content. The density of marrow is different from that of the cavity and is closer than the other 3 materials to the density of bone, making voxel segmentation difficult.

In this study, marrow content measurements differed from the gold standard by less than 10% considering both underestimation and overestimation. The marrow measurements had the lowest accuracy observed. However, these discrepancies were still smaller than the 18% overestimation and 15% underestimation observed by Liang et al.[28] in a CBCT study measuring artificial periapical lesions. These differences between studies may exist because Liang measured smaller volumes than those in the present study. Goo et al.,[29] Su et al.,[30] and Way et al.[31] used CT to evaluate simulated pulmonary nodules, and they observed that accuracy depended on nodule size, with more accurate measurements obtained for larger volumes. Prionas et al.[32] reached similar conclusions using simulated tumors. Marten et al.[33] observed a greater tendency to underestimate nodule volume for smaller nodules. This collective evidence may be relevant, since it indicates that measurements of smaller volumes are less accurate than those of larger ones.

In a CT study of alveolar clefts, errors in volume ranging from 2.5% to 7.6% were found.[34] In contrast, a study of simulated defects revealed lower volume errors of 2% and 0.4% using automated and manual volume measurements, respectively.[35] For the unfilled specimen assessed in the present study, volume measurements varied by less than 5%. Bayram et al.[36] measured condyle volume with CBCT and found a tendency to overestimate or underestimate volumes, although significant differences were not observed. Confirming these findings, Liu et al.[26] measured tooth volumes and also observed that the measurements slightly deviated from the physical volumes, within a range of −4% to 7%. In a canine prostate volume study (with densities typical of water and soft tissue), Havercamp et al.[37] observed that volume was underestimated in all situations compared to the physical gold standard. In the present study, marrow measurements obtained with ITK-SNAP were underestimated relative to the gold standard.

According to Kamburoglu et al.,[21] the accuracy of segmentation relies on the gray value and threshold value entered by the operator. Segmentation can be challenging when the voxels of different structures have similar values. Fabel et al.[38] observed the same situation when segmenting lymph nodes adjacent to tissue of similar density. This may explain why particular difficulty was encountered when segmenting the specimen with intact marrow, as its voxel density is closer to bone density than are the densities of the other 3 materials. This difficulty was more pronounced in the ITK-SNAP program than in the Dolphin software, and the segmentation was also more time-consuming. However, although the ITK-SNAP measurements of the marrow content were the least accurate (with values underestimated by more than 5%), they were also the measurements with the least variation.

Different CBCT systems can produce different measurements even with the same voxel size, as observed in a CBCT study by Sang et al.[39] However, the present study did not show increased accuracy when voxel resolution was increased, since voxel size did not significantly influence the volume measurements.

A recurrent problem with the ITK-SNAP software was that it frequently crashed during use, forcing the operator to close and reopen it to complete the segmentation. This could relate to its open-source nature (which is otherwise an advantage); in contrast, Dolphin requires a paid license for access to the software.

One potential limitation of the present study is that volume measurements were conducted by only 1 examiner. However, since near-perfect intraobserver reliability and good interobserver reliability were obtained for the unfilled specimen, a second examiner was deemed unnecessary. Additionally, in another volume study, Pinsky et al.[35] obtained reliable results even though the examiners had no previous training in CT image analysis, and they concluded that this result suggested that the methods were not examiner-dependent.

In conclusion, both content and software influenced volume measurement accuracy, especially when the contents had gray values similar to those of adjacent tissues, as observed in the results for the marrow-filled samples. Unfilled specimens had the most accurate volume measurements relative to the gold standard.

Acknowledgments

All institutional and national guidelines for the care and use of laboratory animals were followed.

Conflicts of Interest: None

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