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ORIGINAL ARTICLE

Accuracy of ITK-SNAP software for 3D analysis of a non-regular topography structure

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Abstract

Objectives To evaluate the accuracy of ITK-SNAP software for measuring volumes of a non-regular shape structure, using cone beam computed tomography (CBCT) scans, besides for developing a mathematical model to correct the software measurement error in case it existed.

Methods A phantom made by moulding a rubber duck's head was filled with total (38,000 mm^3) and partial volumes of water (7000 mm^3, 14,000 mm^3, 21,000 mm^3, 28,000 mm^3 and 35,000 mm^3), which constituted the gold standards. The sound phantom and the phantom filled with different volumes of water were scanned in a Picasso Trio CBCT unit set at 80 kVp, 3.7 mA, 0.2 mm^3 voxel and 12×8.5 cm field of view. Semi-automatic segmentation was performed with ITK-SNAP 3.0 software by two trained oral radiologists. Linear regression analyzed the relation between ITK-SNAP calculated volumes and the gold standard. Intraclass correlation coefficient was applied to analyze the reproducibility of the method. Significance level was set at 5%.

Results Linear regression analysis showed a significant relationship between ITK-SNAP volumes and the gold standard ($F = 22{,}537.3$, $p < 0.0001$), with an R^2 of 0.9993. The average error found was 4.7 ($\pm$4.3) %. To minimize this error, a mathematical model was developed and provided a reduction of it. ICC revealed excellent intra-examiner agreements for both examiners 1 (ICC = 0.9991, $p < 0.0001$) and 2 (ICC = 0.9989, $p < 0.0001$). Likewise, inter-examiner agreement was excellent (ICC = 0.9991, $p < 0.0001$).

Conclusion The software showed to be accurate for evaluating non-regular shape structures. The mathematical model developed reduced an already small error on the software's measurements.

Keywords Software · Cone beam computed tomography · Three-dimensional imaging · Cross-sectional anatomy

Introduction

Technology is constantly evolving in the most diverse areas of knowledge. The introduction of cone beam computed tomography (CBCT) in the dental field in the late 1990s provided a tridimensional visualization of teeth and skeletal maxillofacial structures with less ionizing radiation and a lower cost when compared to multidetector computed tomography (MDCT). Since then, this technology has been improved, allowing its application in many fields of dentistry to enhance diagnosis and treatment planning [1].

Therefore, several software packages for post-processing of CBCT scans were developed simultaneously with the improvement of such technology [1]. Beside the visualization of the scanned object in multiplanar reconstructions, many softwares have been launched for performing

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segmentation of anatomical structures and pathological lesions for size, shape and volumetric evaluation and, more recently, for producing 3D-printed models [2, 3].

The segmentation process consists of separating a specific element from the surrounding structures of noninterest for better visualization and analysis, constructing tridimensional virtual models [4]. It may variate from manual to automatic segmentation and requires prior knowledge about the form of the structure of interest and intensity of grey values that compose its image [5]. Although the manual segmentation is considered the most accurate, it is highly time-consuming; the automatic method, on the other hand, is fast but can be rather inaccurate [2]. Therefore, the semi-automatic segmentation has been pointed out as the technique of choice since it combines the high efficiency and repeatability of the automatic methods with the experience of an operator [2, 5].

ITK-SNAP is an open source software that has been widely used for semi-automatic segmentation of the upper airways [5–8], maxillary [9] and sphenoid sinuses [10, 11], pulp cavity [12], periapical lesions [1], coronoid process [13], and so forth. Although being employed to evaluate structures of irregular contours, as far as we know, its accuracy was only tested using more regular phantoms like a hollow tube [4] as gold standard. Thus, due to the importance of segmentation for volumetric assessment of complex structures like the paranasal sinuses, we considered that it would be of interest to test the accuracy of an open source software using an irregular-topography phantom as gold standard. Therefore, the aim of this study was to evaluate the accuracy of ITK-SNAP software for measuring the volume of a structure of irregular shape, using CBCT scans. Moreover, we aimed to develop a mathematical model to correct the software measurement error in case it existed.

Materials and methods

Phantom preparation and image acquisition

A rubber duck was used to create an irregular-topography phantom, which was made by moulding the rubber duck's head with alginate as proposed by Kirmeier et al. [14]. Dental alginate (Hydrogum 5, Zhermack, Badia Polesine, RO, Italy) was prepared according to the manufacturer's instructions and placed in a plastic bowl for posterior embedment of the rubber duck's head in it (Fig. 1). After the alginate set, the rubber duck was removed from the alginate, and the mould was removed from the bowl.

Then, the mould was fully or partially filled with water, using a precision pipette LABMAT Soft® (HTL Lab Solutions, Warsow, Poland). These volumes constituted the gold standard for posterior comparison with the values obtained through segmentation. The partial volumes were 7000 mm^3, 14,000 mm^3, 21,000 mm^3, 28,000 mm^3, and 35,000 mm^3. The phantom was scanned three times with each volume of water and empty (total volume of 38,000 mm^3), using a Picasso Trio CBCT unit set at 80 kVp, 3.7 mA, 17-s acquisition time, 62-s reconstruction time, 0.2 mm^3 voxel and 12 × 8.5 cm FOV (field of view). All images were exported in DICOM (Digital Imaging and Communications in Medicine) format.

Image segmentation

The segmentation process was performed with the semi-automatic mode of ITK-SNAP 3.0 software (Cognitica, Philadelphia, PA, USA) (https://www.itksnap.org).

The anterior, posterior, lateral, medial, superior, and inferior limits of the duck's head were delimitated by the examiner in multiplanar reconstructions, defining the region of interest (ROI) for segmentation. Therefore, three user-guided interactive steps were done: a threshold interval was set to determine the starting and ending of the segmentation process, meaning that all voxels with gray values inside that interval would be selected to construct the 3D model. Thresholding selection was interactive, i.e., performed by the operator based on a visual discrimination of the structure's boundaries in each CBCT image. For the partial volumes (phantom scanned with water), the mean and standard deviation (S.D.) of the lower and upper threshold were −405.2 (±43.0) and 152.73 (±13.8), respectively. For the total volume (sound phantom), the mean and S.D. of the lower and upper threshold were −1227.5 (±10.5) and −203 (±38.0), respectively. In the next step, "seeds" were placed in the ROI by the operator to initialize the segmentation; and lastly, the segmentation evolution was run by selecting its

Fig. 1 Rubber duck used to create the phantom, in lateral view (**a**), frontal view (**b**), being molded using a plastic container (**c**)

velocity and end. On finishing this procedure, the software provided the 3D reconstruction of the segmented structure (Fig. 2) and its volume in cubic millimeters (mm^3).

The segmentation was conducted by two oral radiologists trained with the use of the software on a computer display (Dell 14-inch liquid–crystal display monitor with 1366×768 resolution; Dell, Round Rock, TX, USA), in a silent and dimmed-light room. Twenty days after completion of all measurements, 20% of the sample was re-evaluated to analyse the intra-examiner reproducibility.

Statistical analysis

Intraclass correlation coefficient (ICC) was calculated to assess the intra and inter-examiner agreement. Linear regression analysis evaluated the relation between the ITK-SNAP calculated volumes and the gold standard volumes, and a calibration curve was developed. Determination coefficient (R^2) was used to observe the goodness-of-fit of the mathematical model obtained in the linear regression. Pearson correlation (rP) test was used to correlate the estimated volumes and the real volumes (varying from 8900 to 29,490 mm^3) obtained from phantoms created from different rubber toys as further tests to validate the model. All data were statistically analyzed using Graphpad Prism 7.0 (GraphPad Software, La Jolla, CA, USA) and Bioestat 5.0 (Mamiraua Institute, Belém, PA, Brazil) software. Significance level was set at 5% in all tests.

Validation of the method

Two different rubber toys were molded and used to acquire CBCT scans of known volumes, following the same methodology previously described for the rubber duck, to validate the developed mathematical model (Fig. 3). Each rubber toy was filled with five different volumes of water and scanned three times with each volume. Each phantom was also scanned empty (total volume). Therefore, 72 different

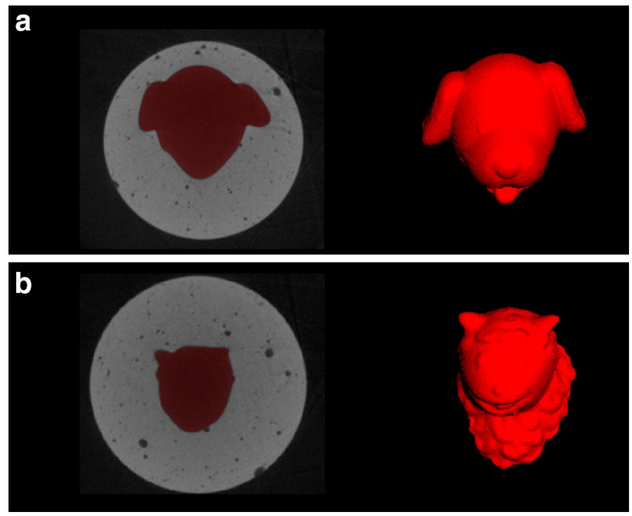

Fig. 3 Coronal reconstructions and 3D volume of the sound phantoms of a rubber dog (**a**) and a rubber sheep (**b**)

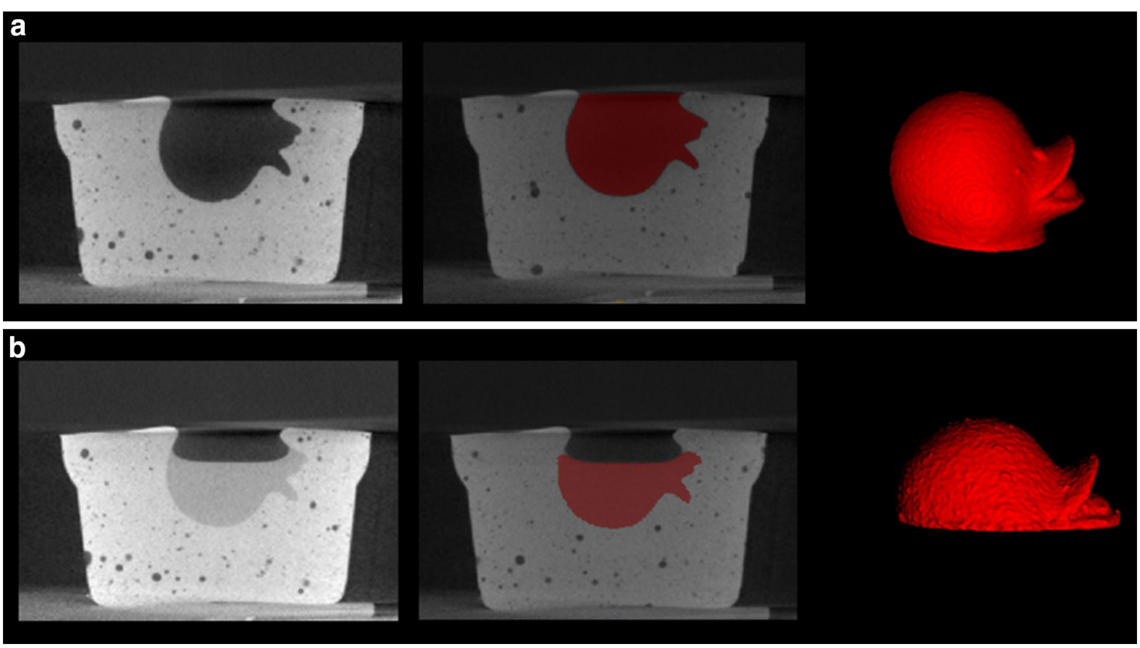

Fig. 2 Sagittal reconstructions and 3D volume of the sound phantom (**a**) and with partial filling of water (**b**)

Table 1 Linear regression model to assess the correlation between ITK-SNAP® calculated volumes and gold standard volumes

	Non-standardized coefficient (*B*)	Standard error	Standardized coefficient (*β*)	*t*	*p* value	Confidence interval 95%
Constant	2.02	162.5	–	0.012	0.99	
ITK-SNAP	0.9969	0.0066	0.9993	150.1	<0.0001	0.98–1.01

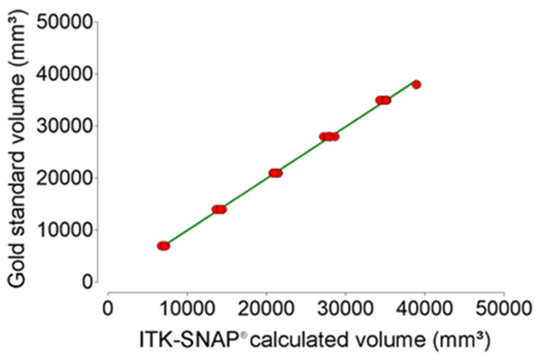

Fig. 4 Correlation between ITK-SNAP calculated volumes and the gold standard volumes

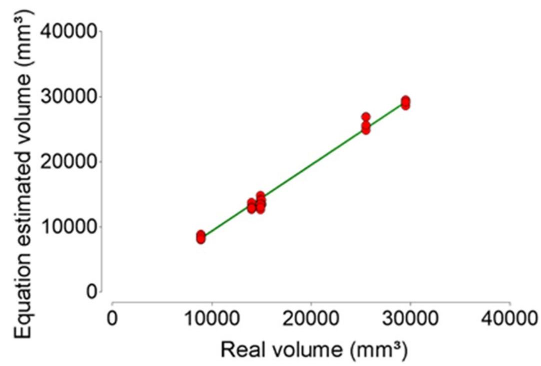

Fig. 5 Correlation between the equation-estimated volumes and the real volumes

scans were totaled, with volumes ranging from 8900 to 29,490 mm^3.

Results

The ICC coefficient showed an almost perfect agreement for both intra- and inter-examiner reliability (0.999, $p<0.0001$), revealing that the examiners' measurements can be interchangeable.

Table 1 shows the relationship between the ITK-SNAP calculated volumes and the gold standard volumes by means of a linear regression model. Figure 4 shows the calibration curve for this analysis.

The linear regression model showed to be highly significant ($F=22{,}537.3$, $p<0.0001$), with an R^2 of 0.9993. The average error between the ITK-SNAP calculated volumes and the gold standard volumes was 4.7 ($\pm$4.3) %, demonstrating that the software was effective for determining the real volume of the analyzed structures. Furthermore, a mathematical model was developed and resulted in the equation:

$$\text{Estimated volume} = 2.02 + (0.9969 \times \text{ITK} - \text{SNAP calculated volume}).$$

When different volumes (from rubber toys phantoms used to validate the model) were calculated with ITK-SNAP and submitted to the equation, it was observed, by means of Pearson's test, a very strong ($R^2=0.9952$), almost perfect, correlation between the equation's estimated volumes and the known volumes (Fig. 4). Therefore, it was observed that the mathematical model minimized the already small error of ITK-SNAP measurements (Fig. 5).

Discussion

The semi-automatic segmentation method of the open source software ITK-SNAP was found to be highly accurate for determining the volume of irregular-topography structures. Moreover, a mathematical model applying an almost perfect correlation model was proposed to correct small uncertainties of ITK-SNAP measurement in case it existed. The almost perfect ICC values indicate high reproducibility of the semi-automatic segmentation method, as found in previous studies [6, 8, 14].

The segmentation process consists of separating a specific element from the surrounding structures of noninterest for better visualization and analysis. In the assessment of maxillofacial structures, the accuracy of this process relies on the CBCT system and its exposure protocols, the surrounding structures in the edges of the specific element analyzed, and the segmentation software used [4, 15]. The reported accuracy for segmentation of craniofacial structures varies, and small field of view (FOV)

CBCT devices generally offer greater image contrast than do units with larger FOV [16, 17]. A large FOV is typically used for orthodontic purposes and it has relatively lower contrast and lower signal-to-noise ratio, which creates a challenging situation for image segmentation [18]. Lower quality images may show blurred edges, not allowing for a sharp and clear separation between structures, which compromises accuracy when volumetric measurements are necessary [19]. Moreover, images acquired with high spatial resolutions usually show sharper edges, while low resolution images may have blurred edges and unclear separation between structures, thus affecting thresholding selection accuracy [20]. Despite using a relatively large FOV (12×8.5 cm) and a voxel of 0.2 mm^3 in our study, we found good correlations between the gold standard volumes and ITK-SNAP volumetric measurements. Thus, ITK-SNAP semi-automatic segmentation tool was able to differentiate structure borders in relatively lower contrast images with a not very high spatial resolution.

Weissheimer et al. [4] employed an acrylic phantom of an oropharynx (a hollow tube) to simulate the upper airway to test segmentation software accuracy. However, such phantom does not reproduce the anatomy of radiolucent and irregular structures surrounded by higher-density tissues, such as the nasopharynx, maxillary and sphenoid sinuses, pulp cavity, and periapical lesions, which are usually evaluated in segmentation analysis [1, 6–11, 21, 22]. Considering that human anatomy is complex and singular for each individual, and that perfect reproductions of complex human structures in in vitro studies are a demanding task, we used a convenient method to reproduce irregular-shaped structures: the rubber duck phantom proposed here was an attempt to simulate the curved and non-regular anatomy of maxillofacial structures. Although phantoms based on patients data and created by 3D printing technology have been used to validation studies in CBCT [23], it is not a highly accessible approach due to high cost of printer devices.

Scanning the sound phantom and the phantom filled with water allowed for the evaluation of regions with different image densities. One of the steps in the segmentation process is the determination of a threshold interval, which means that all voxels with grey values inside that interval will be selected to construct the 3D model [4]. Thus, it is easier to separate the element of interest from the surrounding structures when they have different densities than when their densities are similar. Since the density of water is similar to that of the alginate, thresholding and segmentation became harder to perform for the phantoms filled with water. Nevertheless, our results showed a great relationship ($R^2 = 0.9987$) between the ITK-SNAP measurements, with the use of an interactive threshold, and the gold standard, highlighting that the software was efficient to separate the water from alginate.

ITK-SNAP provides a basic set of algorithms that can be used to develop and customize a full segmentation application, as such as level-set method, that is a numerical method for tracking the evolution of contours and surfaces. Instead of manipulating the contour directly, the contour is implanted in a level-set function, so arbitrarily complex shapes can be modeled and such topological changes are handled implicitly, which allows the segmentation of complex geometry of the maxillofacial structures. Using level-set method of ITK-SNAP we evaluated the accuracy of its semiautomatic segmentation in CBCT images of an object of non-regular topography [24].

The ITK-SNAP segmentation tool is based on a level-set algorithm. Level sets can be employed for image segmentation using image-based features in a differential equation. In a typical approach, a contour is initialized by the user and, then, it is evolved until it fits the form of the anatomical structure in the image. In this study, the segmentation process started from user-provided seeds inside the object of interest (anatomical structure), spreading (pixel-by-pixel) by region growing algorithm, based on user-determined threshold, until it reached the structure's boundaries. A geodesic active contour algorithm is used to attract the level set to the object boundaries where areas of high curvature are smoothed out, providing better structure edges preservation [24].

Whereas no measurement method is absolutely accurate, our research revealed 4.7% average error of ITK-SNAP. As a way to minimize this already small error, we developed a calibration curve reflected in a mathematical model and based on the logistic regression analysis. This mathematical model proved to reduce the error of ITK-SNAP measurements for structures with volumes ranging from 7000 to 38,000 mm^3. It is important to have in mind that the correction employed by the mathematical model was small, reinforcing that the values rendered by ITK-SNAP alone were already close to the real measurements.

On the results of Weissheimer et al. [4], ITK-SNAP showed less than 2% error compared with the gold standard. Mimics®, Dolphin3D® and OsiriX® showed similar results to ITK-SNAP, while Ondemand3D® and InVivo Dental® showed an error greater than 5%. In other studies, Fyllingen et al. [25] revealed a 5.5% error for ITK-SNAP when assessing the volume of brain tumors, while Lee et al. [26] showed a precision value of 0.934 ± 0.037 for ITK-SNAP on cerebellar volumetric measurement, but both using magnetic resonance imaging.

The level of error found in our study is greater than that reported by Weissheimer et al. [4]. This seemingly poorer result may be explained by the greater complexity of the structure assessed by us, which makes the segmentation process harder. However, the error found in our study is relatively small when considering structures of large volumes such as maxillary sinus (13,590 mm^3) [27], pharynx (22,840 mm^3) [6], frontal sinus (2615.4 mm^3) [28], and nasal cavity (9932 mm^3) [29], and it may not have a clinical significance in the volumetric assessment of such. Since the mathematical model only provides a slightly correction, it is up to the professional to employ it or not.

As this study was the first to develop a mathematical model for the purpose of volumetric error correction and we have validated it with scans of other non-regular shapes but not with other software, we strongly suggest that other segmentation software be tested. Therefore, correction models can be devised and increase volumetric measurement accuracy, improving diagnosis and treatment planning in Dentistry.

In conclusion, semi-automatic segmentation using level-set method in ITK-SNAP software accurately determines the volume of non-regular topography structures. Moreover, the mathematical model presented here can further minimize the small error seen with ITK-SNAP measurements alone.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human/animal rights This article does not contain any studies using human or animal subjects.

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