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A novel image processing technique for three-dimensional volumetric analysis of severely resorbed alveolar sockets with cone beam computed tomography.

Valeria Manavella,[1] Federica Romano,[1*] Federica Garrone,[2] Mara Terzini,[3] Cristina Bignardi,[3] Mario Aimetti[1]

[1]Section of Periodontology, C.I.R. Dental School, Department of Surgical Sciences, University of Turin, Turin, Italy; [2]Private practice, Turin, Italy; [3]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy.

Corresponding author: dr. Federica Romano, Section of Periodontology, C.I.R. Dental School, Via Nizza 230 10126 Turin (Italy) email: federica.romano@unito.it

ABSTRACT

BACKGROUND: The aim of this study was to present and validate a novel procedure for the quantitative volumetric assessment of extraction sockets that combines Cone-Beam Computed Tomography (CBCT) and image processing techniques.

METHODS: The CBCT dataset of 9 severely resorbed extraction sockets was analysed by means of two image processing software, Image J and Mimics, using manual and automated segmentation techniques. They were also applied on 5 mm spherical aluminum markers of known volume and on a polyvinyl chloride model of one alveolar socket scanned with Micro-CT to test the accuracy.

RESULTS***:*** Statistical differences in alveolar socket volume were found between the different methods of volumetric analysis ($P < 0.0001$). The automated segmentation using Mimics was the most reliable and accurate method with a relative error of 1.5%, considerably smaller than the error of 7% and of 10% introduced by the manual method using Mimics and by the automated method using ImageJ.

CONCLUSION: The currently proposed automated segmentation protocol for the three-dimensional rendering of alveolar sockets showed more accurate results, excellent inter-observer similarity and increased user friendliness. The clinical application of this method enables a three-dimensional evaluation of extraction socket healing after the reconstructive procedures and during the follow-up visits.

Key words: Bone resorption - Cone beam computed tomography – Periodontitis - Tooth socket - Volume.

Introduction

The fresh extraction socket in the alveolar ridge represents a special challenge in every-day clinical practice. Regardless of the subsequent treatment, maintenance of the ridge contour will frequently facilitate all further steps of therapy. This is particularly true for treatments involving the placement and reconstruction of dental implants.[1]

During the spontaneous healing phase the extraction socket undergoes a rapid resorption in horizontally and vertically direction that in the first 2 years reaches percentages of 40-60% in intact sockets.[2,3] In advanced periodontitis patients alveolar sockets often exhibit severely resorbed buccal/lingual bone plate and loss of interproximal attachment level.[4] In such extraction sites with significant breakdown of the bony socket walls, it is recommended to perform reconstructive procedures to restore appropriate ridge shape and volume before or in conjunction with implant placement.[5,6]

Nowadays, the morphology of the residual alveolar crest as well as the outcomes of the reconstructive treatment are assessed clinically or radiographically on intraoral periapical radiographs or cone-beam computed tomography (CBCT).[7-10] However, they provide clinicians only with vertical and horizontal linear measurements that poorly reflect the three-dimensional (3D) aspect of bone resorption.[11] The accuracy of linear measurements of CBCT has been previously assessed in cadavers and standardized phantoms.[12-16]

Another aspect to take into account is that these measurements are usually calculated as distance between anatomic landmarks.[17] As previously demonstrated in cephalometric analysis, manual landmark plotting on a 3D image is a challenging task that influences dimensional analysis in terms of accuracy and reliability.[18] It is likely to expect that measurement errors are higher when considering anatomic structures that undergo active remodelling during the healing phase. This is even more relevant when considering severely adsorbed alveolar sockets that exhibit complex 3D anatomy due to buccal/lingual wall deficiency.

Hence, there is a need to develop a method of image processing which can provide accurate and reliable 3D measurements and could be used in clinical practice. Therefore, the aim of this study was to present and validate a novel protocol that combines CBCT and image processing techniques for 3D volumetric analysis of post-extraction alveolar sockets. It was applied to severely resorbed alveolar sockets due to advanced periodontitis.

Materials and methods

Nine patients (6 women and 3 men, mean age 48 ± 12 years) with generalized chronic periodontitis who required the extraction of at least one hopeless tooth for periodontal reasons in the anterior and premolar upper region were consecutively enrolled in the study. The study protocol had institutional review board approval (protocol n° 695/2015) and all subjects were asked to provide informed consent to participate after a detailed explanation of the procedures and objectives of the study. After the initial periodontal non-surgical therapy, minimally traumatic extractions were performed. The sockets were thoroughly degranulated and examined for the presence of buccal wall deficiency as described by Jung et al.[7] The height of the buccal and lingual bone plate was clinically measured at the midbuccal and midlingual aspect to the base of the socket by using a periodontal probe. Therefore, it was possible to calculate the vertical loss of the buccal plate compared with the palatal bone wall. If >50% of the socket wall was absent, the site was included in the study. Immediately after extraction a CBCT was taken (New Tom/NTVG; slide thickness = 0.4 mm; scan time = 10 s, field of view = 153.60 mm; pixels size = 0.3 mm; 110 kV; 2 mA) with a custom-made template in acrylic resin containing 3 aluminum radiopaque markers used as reference tool to standardize measurements (5 mm high-precision ball, volume 65.5 mm^3, Martin & C. srl, Italy). Images were exported in DICOM (Digital Imaging and Communications in Medicine) format to Mimics 17.0 (Mimics Innovation Suite®, Materialise NV, Belgium) and ImageJ (National Institute of Health, USA) software to quantify the alveolar socket volume by one operator with extensive experience.

Accuracy of Image processing with Mimics 17.0 on high-precision spherical markers

For each CBCT dataset, the image processing techniques were first implemented on the radiopaque markers using Mimics 17.0 software. Manual and automated segmentation methods were exploited. This was done to test the accuracy of CBCT volume measurements by comparison with direct volume measurements of the same markers. Selected images were enhanced with adjust contrast and smoothing tools to make them more suitable for the operation of thresholding. Both segmentation procedures rely on the thresholding technique that classifies all pixels, included in a range of grey values as belonging to a specific mask from which it is possible to extract the object of interest. The threshold was determined case-by-case. When selecting threshold grey values ≥ 360 all pixels belonging to alveolar bone, teeth and markers could be labelled in a single mask, whereas for grey values < 360 those belonging to soft tissues and background (Fig. 1).

Manual segmentation

The mask obtained by the thresholding operation was limited in each slice exclusively to the region of interest (ROI), making it sure to have rebuilt manually the boundaries of the marker.

Automated segmentation

This technique relies on the implementation of the Region Growing Segmentation algorithm on the mask limited to the structures of interest obtained by a Boolean subtractive operation between the background and the mask of the marker. Primarily, both the background (including soft tissue) and the mask of the marker (including dental and alveolar tissues) were created with the thresholding procedure. Then, by applying a Boolean subtractive operation between the two masks, it was possible to obtain a third mask in which all pixels with similar intensity were identified quickly and iteratively by the Region Growing algorithm and appended gradually inside the marker. Instead of thresholding, the technique of Region Growing is capable of identifying the ROI by looking for groups of pixels that respond to homogeneity criterion and spatial connection.

Image Rendering

The rendering operation, required for 3D reconstruction and quantitative volume assessment, was applied to the segmented images of 8 markers. It was done using the 'Calculate 3D' tool that allows for the creation of an accurate 3D model from 2D data previously processed (Fig. 2a-b).

Volumetric analysis of post-extraction alveolar sockets

The same segmentation methods applied to the markers were implemented for the volumetric assessment of post-extraction alveolar sockets. From CBCT datasets only the stack of the whole alveolar sockets was selected, taking as landmark the root apex of the adjacent teeth and the interdental bone peaks. After pre-processing operations, the alveolar socket was segmented with both the manual and automated procedure. When the manual method was employed, great care was taken in tracing its whole profile. On the contrary, when using the automated segmentation it was needed to rebuild only the buccal wall damaged by the periodontal disease but not the whole socket cavity. Finally, the rendering operation and the volume assessment were done (Fig. 3). In order to assess inter- and intra-operator reliability, the automated segmentation method was repeated 5 times per alveolar socket by 5 different observers. Observers 1 and 2 had extensive experience with the segmentation of alveolar sockets based on CBCT data, whereas observers 3 and 4 had intermediate experience. Observer 5 had extensive clinical experience in analysing CBCT images but not in implementing image processing techniques. The segmentation results of the observers were referred to as Segmentation Group 1 (SG1) for observer 1 through Segmentation Group 5 (SG5) for observer 5. The same procedure was also applied to assess the inter-observer variability in the selection of the threshold values.

ImageJ image processing

To test the reproducibility of data obtained with Mimics 17.0 software, the images of the alveolar sockets were also processed with the open-source ImageJ software that is widely used in dentistry. After enhancing contrast and smoothing operations, the threshold was properly determined to distinguish the ROI from the background. The objective was to obtain a stack of binary images in which soft tissue and background were represented by black pixels, while hard tissue by white pixels.

After manual tracing of the hard tissue lining of the damaged alveolar walls, it was possible to proceed with the segmentation and so with the assessment of the area subtended by the black pixels representing the alveolar socket. Finally, these values were summed and multiplied by the thickness of the slices to obtain the volumetric measurements.

Volumetric analysis of a PVC model of a severely resorbed alveolar socket

The effective size of the alveolar sockets are not known then, in order to evaluate the error made in quantifying the volume by using a CBCT image processing technique, among those analyzed, a severely resorbed alveolar socket was chosen and its physical volume was realized. In fact, from the virtual 3D reconstruction by means of image processing technique, it was possible to derive the STL files necessary to realize, by means of subtractive rapid prototyping process by using the CNC milling machine Roland MDX-40 SRP® (Roland DG Mid SR L Europe, Italy), a polyvinyl chloride (PVC) model. This model reproduces with a good precision (0.002 mm/step) the geometry of the alveolar socket chosen and it is possible to accurately assess its volume. Later, it was made a Micro-CT (1174v2, scan resolution: 11.4 m; exposure time for every angle: 2400 ms; angle: 0.3 °; Bruker, Belgium) of this model, and finally the Micro-CT images were analyzed with the same image processing procedures used in the analysis of CBCT images.

Data analysis

Based on the Shapiro-Wilk test for normality, the one-way ANOVA was performed to compare the volume of 9 alveolar sockets as measured with the three image processing methods, considering the absence of difference between them as null hypothesis and using post-hoc test (Bonferroni t-test) to investigate any difference. Volume measurements were repeated 5 times per each alveolar socket by the most experienced operator and compared.

Intra- and inter-examiner agreement was assessed by means of the intra-class correlation coefficient (ICC). An ICC <0.40 was considered as poor, 0.40–0.59 as fair, 0.60–0.74 as good, and 0.75–1.00 as high.

To evaluate the error of each method of image processing, the corresponding segmentation volumes were compared to the known volumes of the radiopaque markers and of the PVC model using the paired *t*-test. The level of significance was set at 0.05 for all tests. Statistical analysis was performed with Graphpad Prism6.

Results

Figure 5 summarizes the volumes of radiopaque markers as measured by manual and automated segmentation procedures using Mimics 17.0. The average volume was 69.76 ± 3.43 mm^3 for the manual technique and 68.33 ± 2.87 mm^3 for the automated method, with a relative error of 6.50% and 4.32%, respectively. The differences between the two procedures were statistically significant favouring the automated procedure (P = 0.025).

Of 9 sockets in the upper jaw, 4 were central incisors, two lateral incisors, one canine and two first premolars. All displayed a buccal bone loss > 50%. The height of the residual bone plate at the mid-buccal aspect was 1.7 ± 1.2 mm. A summary of volumetric measurements of the 9 segmented alveolar sockets with different morphology is given in Table I. As reported in Figure 6 significant statistical differences in alveolar socket volume were found between the three methods of volumetric analysis ($P < 0.0001$). The greater difference in alveolar volume was observed between the automated and manual segmentation methods by Mimics ($P = 0.0068$) with a mean difference of 13.35 mm^3 (Fig. 7a-b). Conversely, no statistically significant differences were observed between the two automated techniques.

With regard to the intra- and inter-examiner reliability all the values for the ICC were > 0.85, showing the high reproducibility of the measurements (Fig. 8). The mean volumetric difference of alveolar sockets between SG1 and SG5 was 4.64 mm^3 resulting an ICC of 0.91.

The mean threshold values set by 5 different operators are summarized in Table I. All grey values were greater than 360 and ranged between 436.6 and 1041.6 with the greatest difference of 72.76 detected between SG1 and SG5 ($P = 0.1213$).

To test the accuracy of the three segmentation techniques in the 3D reconstruction of severely resorbed extraction sites, all were applied to the Micro-CT dataset of the PVC model of one of the 9 alveolar sockets. The Micro-CT scan yielded a volume of 317.05 mm^3 that differed by 19.4 mm^3 from the STL files (Fig. 9). Both the automated and manual methods using Mimics obtained a volume of 307.35 mm^3, whereas the automated technique with ImageJ yielded a volume of 317.02 mm^3. The same volumes were 312.13 mm^3, 340.21 mm^3 and 283.75 mm^3 when such segmentation techniques were applied on the CBCT dataset of the same alveolar socket. The relative error was computed from the reference value of the PVC model. The relative error induced by the automated segmentation protocol using Mimics was 1.5%, considerably smaller than the error of 7% and of 10% introduced by the manual method using Mimics and by the automated method using ImageJ, respectively.

Discussion

The aim of this study was to describe a method to assess changes in hard tissue volume and profile by volumetric analysis based on the implementation of image processing techniques in software for 3D design. This is particularly relevant when considering severely adsorbed alveolar sockets that exhibit complex morphology due to the advanced damage of the bony walls. The applicability of Mimics software for alveolar volumetric analyses *in vivo* has not been addressed before. A recent paper evaluated the reproducibility of 3D reconstruction of palatal cleft defects using a semi-automated technique to define 4 masks of the relevant bone structures and considering cephalometric landmarks to identify a reference plan.[19] This segmentation technique is more complex than that described in the present paper and does not eliminate the need for a manual contouring of anatomic boundaries.

The proposed segmentation method using Mimics was compared to ImageJ, a freely downloadable image analysis package that had been developed by the National Institute of Health to assist in clinical and scientific image analyses and has been widely used in the dental literature. Previous *in vitro* studies demonstrated a good accuracy in ImageJ 3D volumetric analysis on dry skull mandibles.[20,21]

In order to test their accuracy, automated and manual segmentation procedures using Mimics were applied to dataset of spherical radiopaque markers with known volume. The two methods achieved similar results. The most likely explanation relies on the shape of the volume-of-interest (VOI) as well as on the position of the markers in the CBCT template. The simple and regular morphology required less interpretation in the contours and thus it simplified the implementation of the manual segmentation procedure. As the markers were far from teeth and anatomic structures that present similar grey scale, they were easily recognized with both the methods. Another important factor to take into account is the resolution of the stack and, in particular, the distance between the slices. Indeed, images with a thickness of 0.4 mm hindered the full recognition of the 5 mm spherical markers so that they appeared without the boundaries. In previous *in vitro* studies no significant differences were found between slice thickness of 0.3 mm and 0.4 mm in hard and soft tissue measurements.[22,23]

But as in many cases needed by a dentist the shape of the VOI is irregular, the same procedures of image processing were implemented for the segmentation of severely resorbed alveolar sockets. A significant statistical difference in alveolar socket volume was found between the three methods of volumetric analysis. The greater difference in alveolar volume was observed between the automated and manual segmentation methods by Mimics whereas the two automated techniques achieved comparable results. Although methodologically simple, the manual segmentation procedure using Mimics has some main limitations such as heavy time demands for images processing, high measurement variability and high potential for operator bias due to the need of manual tracing of the whole profile of intact/injured alveolar socket and to the over or under-segmentation attributable to the poor detection of the target structure. Indeed, it is important to underline that the manual segmentation is largely related to the fruition of the image which might mislead the operator during the image processing. Consequently, this imaging technique is prone to errors due to noise and fatigue with high intra- and inter-operator variability. Manual segmentation works relatively well for VOI of simple and regular shape and with very good contrast between distinctive sub-regions.

Conversely, the automated technique, regardless of the software used, is more simple and feasible and is better suited for segmentation of alveolar sockets because the operator is required to manually trace only the buccal bony wall, while an algorithm identifies the remaining structural parameters with high precision. The human eye can discriminate between about 16 grey levels at a time, whereas the numerical algorithm has the capability to discriminates between different tissues with similar grey levels intensity values by computing the corresponding pixel intensities on CBCT images.

Both automated segmentation techniques depend strongly on the proper selection of the threshold values that affect the accuracy of 3D volumetric assessment and reconstruction of the post-extraction alveolar sockets. The distribution of intensities in alveolar CBCT images is usually very complex, and determining a threshold is difficult. A too selective threshold increases the risk of not detecting the ROI. When the threshold is chosen too low it is not possible to discriminate the target tissues from the surrounding ones and this leads to a higher over-recognition rate. The comparison between the two automated segmentation techniques, implemented with ImageJ and Mimics, did not demonstrate any statistically significant difference. This is likely due to the algorithms used during the pre-processing and thresholding procedures. Of note, the more automated nature of the segmentation protocol with Mimics reduced the magnitude of the observer-related errors. Thus, it resulted in high intra- and inter-individual reliability even when implemented by operators with different degrees of experience.

Finally, to test the accuracy of the segmentation protocols they were applied to the Micro-CT images of a PVC model of a severely resorbed alveolar socket made with a rapid prototyping subtractive process. The differences in volumetric measurements were minimal when compared to the known volume. Possible explanations are the high Micro-CT resolution, of about 11.4 μm, which allows for the complete recognition of the object of interest, and the high contrast of the images provided at air/object interfaces. When dealing with CBCT images it is more difficult to distinguish the boundary between dental alveoli and surrounding tissues due to the similar grey levels.

Of note the comparison between volumetric data obtained by implementing the segmentation techniques on the CBCT and Micro-CT images of the same alveolar sockets demonstrated a relative error of 1.5% for the automated procedure with Mimics. This percentage increased to 10% for ImageJ software due to the difficulties in properly discriminating hard from soft tissue when processing images of more complex 3D geometry. Soft tissue is known to cause X-ray scatter with associated streak artefact. X-ray scatter reduces the contrast-to-noise ratio and the accuracy in reconstruction value.[24]

Limits of the present study are the difficulty in determining threshold values to distinguish the boundary between dental alveoli and surrounding tissues and the error in manually tracing the profile of the resorbed bone. Data from the literature have demonstrated that it is not possible to set a standard grey value for alveolar bone due to different types of artefacts, the cone beam geometry and the limited size of the field of view.[10,25] Although a manually defined threshold setting for each CBCT data set may be less reproducible than the use of an automatically approach, it was demonstrated to generate fewer errors in the determination of the alveolar bone defect volume.[26]

Precise definition of the 3D anatomical boundaries of the alveolar bone defect is essential. In the present study the contours of the resorbed buccal wall were outlined manually. However, in a study on alveolar bone defects in cleft lip and palate patients the error was found negligent/small when the buccal and palatal boundaries of the defects were manually traced.[19]

Another important issue is the impossibility to compare the radiographic 3D reconstruction of post-extraction sockets with their known volumes. However, the possibility to favourably compare the present *in vivo* results, obtained using the automated procedure implemented with Mimics, with volumetric 3D analyses present in the literature on human dry skulls further corroborates the reliability and the potential applicability of the proposed method.[27]

Conclusions

This study was aimed to propose a novel procedure for quantitative volumetric assessment of post-extraction alveolar sockets that combines CBCT and image processing techniques. The automated segmentation technique with Mimics showed more accurate results in 3D measurements of severely resorbed alveolar sockets, an excellent inter-observer similarity, and increased user friendliness. However, a relative error of about 1.5% was observed mainly due to the selection of the proper threshold value.

Conflicts of interest: The authors declare that they have no conflict of interest.

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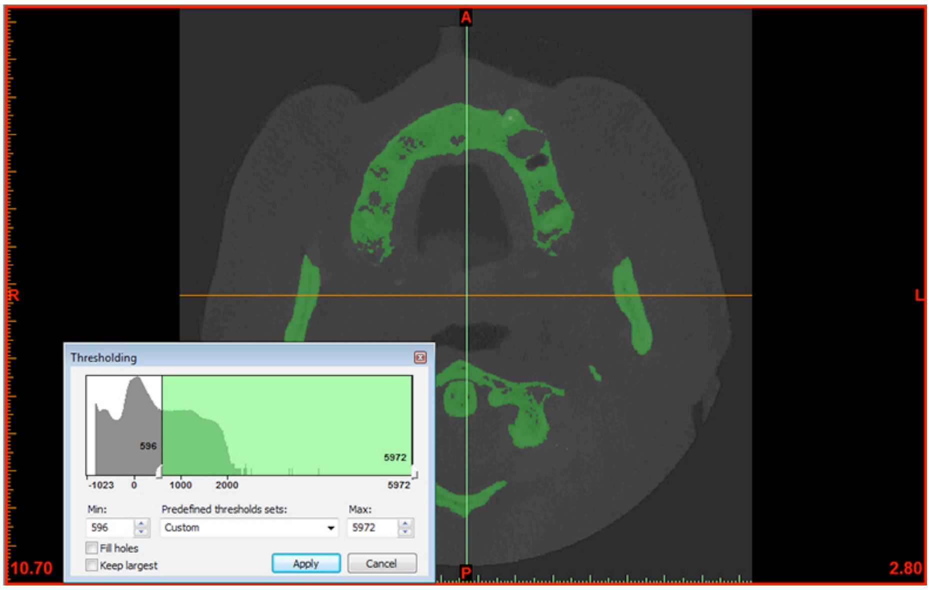
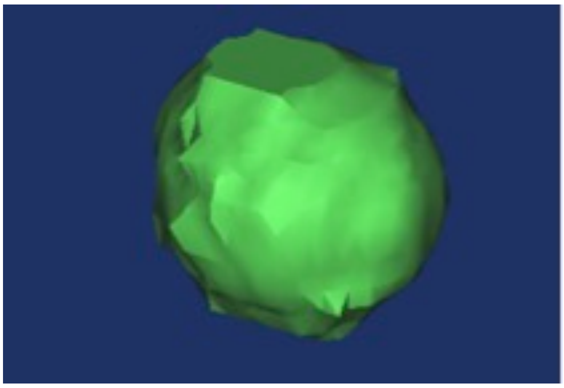


Fig. 1



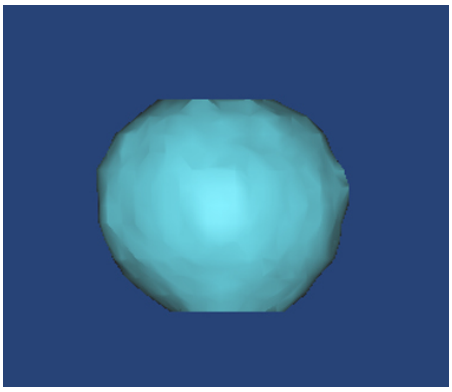
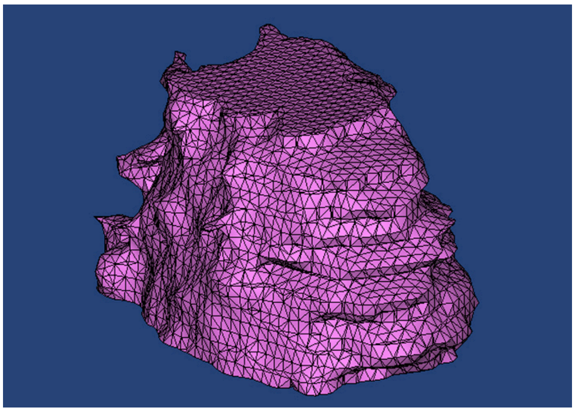


Fig. 2a

Fig. 2b



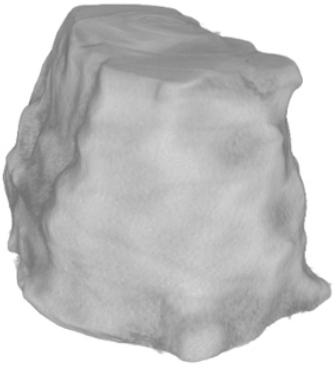
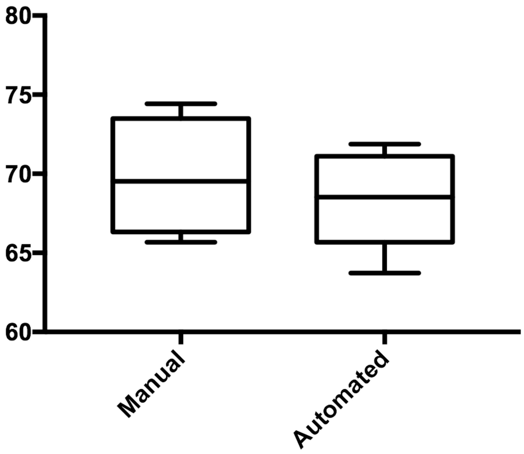


Fig. 3

Fig. 4



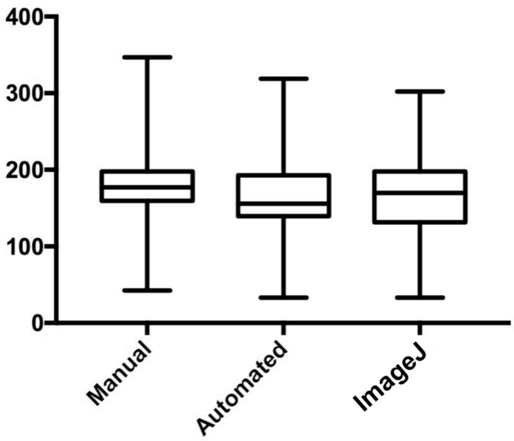
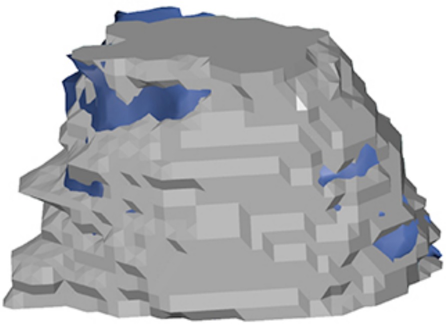


Fig. 5

Fig. 6



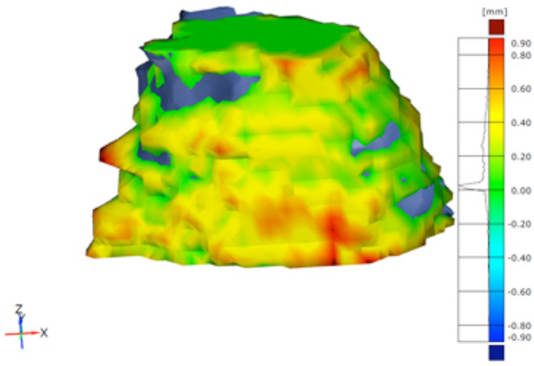


Fig. 7a

Fig. 7b

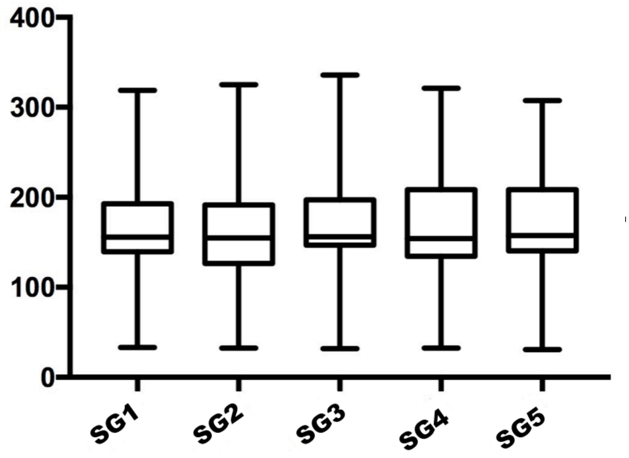

400
300
200
100
0
SG1
SG2
SG3
SG4
SG5

Fig. 8

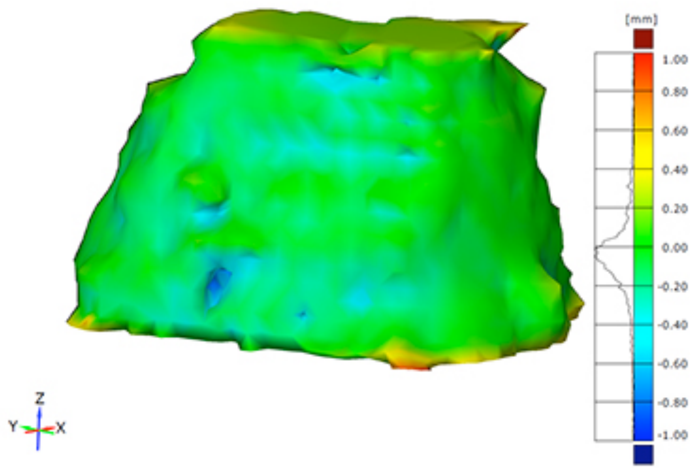

[mm]
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Z
Y
X

Fig. 9

Table 1. Volumes of 9 alveolar sockets calculated with different segmentation techniques.

	VOLUME (mm^3)											
	MANUAL MIMICS	AUTOMATIC IMAGEJ	AUTOMATIC MIMICS[a]									
ALVEOLAR SOCKETS			SG1	Grey value	SG2	Grey value	SG3	Grey value	SG4	Grey value	SG5	Grey value
# 1	232.64 ± 4.07	201.43 ± 11.48	237.14 ±12.56	1041.6	218.09 ± 8.68	912.8	193.74 ± 8.32	804.8	216.08 ± 6.49	953.2	223.40 ± 8.69	1008.8
# 2	340.21 ± 7.50	283.75 ±19.37	312.13 ±5.99	472.8	322.90 ± 3.72	512,0	325.45 ± 8.63	554.2	313.55 ± 7.72	496.0	300.62 ± 4.01	459.8
#3	142.92 ± 8.99	130.01 ± 1.82	127.12 ±5.05	470.4	127.23 ± 4.71	436.6	128.33 ± 2.19	476.4	127.12 ± 3.55	469.0	130.69 ± 3.43	511.8
#4	175.34 ± 6.00	178.20 ± 7.10	153.19 ±3.52	538.8	132.86 ± 7.03	545.6	154.53 ± 4.56	583.8	153.35 ± 7.37	564.4	158.76 ± 3.31	668.6
#5	177.27 ± 2.79	140.57 ± 16.27	153.37 ±2.33	753.2	126.31 ± 3.74	622.2	151.84 ± 4.39	754.0	140.72 ± 11.42	719.4	145.77 ± 5.11	746.8
#6	162.31 ± 2.75	152.90 ± 1.53	142.02 ±2.43	558.0	150.70 ± 9.03	607.2	151.85 ± 4.26	661.0	144.05 ± 3.67	569.0	154.63 ± 3.54	701.4
#7	46.95 ± 3.65	36.19 ±2.04	35.97 ±2.58	439.6	35.51 ± 2.78	380.8	34.89 ± 2.33	466.0	33.83 ± 1.97	450.6	33.04 ± 1.33	427.0
#8	182.71 ± 11.54	172.38 ± 14.82	173.58 ±11.79	729.4	169.32 ± 7.27	680.2	162.87 ± 4.57	681.2	169.93 ± 3.65	700.6	163.51 ± 8.96	663.2
#9	89.74 ± 2.92	198.88 ± 3.74	191.80 ± 1.64	415.4	189.93 ± 2.34	417.8	198.36 ± 1.55	511.4	203.05 ± 5.2	574.4	204.15 ± 4.56	582.6

[a] Each socket was analysed 5 times with the same technique by 5 operators (SG1 through SG5). Data are expressed as mean ± SD.