RESEARCH ARTICLE

Assessment of automatic segmentation of teeth using a watershed-based method

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Objective: Tooth 3D automatic segmentation (AS) is being actively developed in research and clinical fields. Here, we assess the effect of automatic segmentation using a watershed-based method on the accuracy and reproducibility of 3D reconstructions in volumetric measurements by comparing it with a semi-automatic segmentation (SAS) method that has already been validated.

Methods: The study sample comprised 52 teeth, scanned with micro-CT (41 µm voxel size) and CBCT (76; 200 and 300 µm voxel size). Each tooth was segmented by AS based on a watershed method and by SAS. For all surface reconstructions, volumetric measurements were obtained and analysed statistically. Surfaces were then aligned using the SAS surfaces as the reference. The topography of the geometric discrepancies was displayed by using a colour map allowing the maximum differences to be located.

Results: AS reconstructions showed similar tooth volumes when compared with SAS for the 41 µm voxel size. A difference in volumes was observed, and increased with the voxel size for CBCT data. The maximum differences were mainly found at the cervical margins and incisal edges but the general form was preserved.

Conclusion: Micro-CT, a modality used in dental research, provides data that can be segmented automatically, which is time saving. AS with CBCT data enables the general form of the region of interest to be displayed. However, our AS method can still be used for metrically reliable measurements in the field of clinical dentistry if some manual refinements are applied.

Dentomaxillofacial Radiology (2018) **47**, 20170220. doi: [10.1259/dmfr.20170220](https://doi.org/10.1259/dmfr.20170220)

Cite this article as: Galibourg A, Dumoncel J, Telmon N, Calvet A, Michetti J, Maret D. Assessment of automatic segmentation of teeth using a watershed-based method. *Dentomaxillofac Radiol* 2018; **47**: 20170220.

Keywords: Cone-beam computed tomography; X-ray microtomography; three-dimensional imaging; automatic segmentation; semi-automatic segmentation.

Introduction

Imaging is an important complementary part of clinical dental practice and research. Measurements of dental arches, teeth, or parts of a tooth, such as the root canal, are important in many dental disciplines (orthodontics, implantology and endodontics). To obtain such measurements, a segmentation process has

to be used to locate and analyse anatomical structures and their boundaries in images.¹ 3D segmentation is an imaging process that allows a group of voxels to be extracted from the rest of the data using their intensity and density.² Accurate segmentation and the resulting classification of different anatomical structures are relevant in clinical dental practice.

The reference technique for acquisition in 3D dental research is micro-CT.^{3–6} In clinical dental practice, the volume examined requires a sufficiently large field of

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Received 07 June 2017; revised 20 August 2017; accepted 13 September 2017

view and the dose of radiation to be received by a living subject is limited by the International Atomic Energy Agency. The technique for acquisition in dental practice is CBCT, which, with a relatively low dose of radiation, provides a spatial resolution that varies from 70 to 600 μm according to the field of view⁷ and its use is widespread. If volumetric measurements are to be used, *e.g.* for clinical applications (dental volume, bone volume) and in the medico-legal field with the estimation of age from the dental volume, it is necessary to validate CBCT against the gold standard of micro-CT in a methodological approach. The reference-imaging tool for dental research and anthropological and forensic data on the dental organ remains micro-CT.^{8–13}

Segmentation is interesting because it can provide a variety of information to the dentist. For example, the root canal anatomy is easier to apprehend after segmentation.¹⁴ A surgical approach to periodical cysts is more precise after tooth, cyst and bone segmentations.¹⁵ Tooth segmentation is helpful to visualize the positions of roots, and not only crowns, when carrying out orthodontic treatment.¹⁶ Dental researchers are thus turning their attention to this technique in the hope of finding the most reliable method for automatic segmentation (AS). Among the various possible uses of a segmentation, such as the volume shape or the linear measurements, the calculation of the volume is also of interest. In legal odontology, the volume of a tooth gives access to an estimate of the age of an individual.⁸ Clinically, CBCT data can be used after segmentation for several odontological disciplines.¹⁷ In orthodontics, the calculation of the volume of a tooth makes it possible to monitor the appearance or the evolution of the external root resorption.¹⁸ It also allows the remaining intraosseous tooth volume to be calculated and the behaviour of the centre of resistance of the tooth to be better predicted.¹⁹ In implantology, the segmented bone volume or segmented sinus volume makes it possible to predict the dose and even to machine the exact volume of bio-material intended to reconstitute the bone volume in pre-implant.²⁰ The volume segmented can also be used to mimic the transgingival root volume to obtain an optimal implant prosthetic abutment.^{21,22}

We can define three main techniques of segmentation. Manual segmentation, the standard way to segment teeth, requires manual labelling of each anatomical structure. This is a time-consuming task that needs an experienced clinical operator. Semi-automatic segmentation (SAS) extends the selection of the voxels of the ROI (region of interest) through several slices and an additional manipulation is necessary to correct under or over segmentation. This method, which consumes less time in segmentation, requires anatomical knowledge. Given the complexity of the anatomical structures and their surrounding tissues, Wang *et al*²³ suggest that AS, although a difficult task, would be promising. Today, processing algorithms to achieve AS are being actively developed.^{2,23,24} After setting adjustments on

the ROI, these automatic procedures perform segmentation without manual intervention. The advantage of this method would be to process large volumes of data because it is less operator dependent. The main difficulties in automatic medical image segmentation are the lack of spatial resolution and contrast of the images. For this reason, an ideal segmentation method does not exist. Many computer imaging segmentation tools with different mathematical models exist. Thresholding, edge or region based detection, methods using 2D or 3D preforms, level-set, or hybrid methods are found.^{23,25}

We hypothesized that, with AS, volumetric measurements of teeth would be the same as with SAS using micro-CT and CBCT with different voxel sizes.

To limit bias in connection with differences in the images obtained by CBCT, we used our method on data provided by the reference technique for acquisition. In 3D dental research and measurements, this reference is micro-CT imaging.^{3–5,26} In dental practice, although AS would be useful, its accuracy has to be assessed. So we chose to compare SAS micro-CT volumes with those from the AS method under test, using CBCT images of different voxel sizes.

The aims of our study were, first, to assess the accuracy of our volumetric measurements in micro-CT and CBCT images by comparing AS and SAS methods and, second, to visualize the topography of the geometric differences in 3D micro-CT reconstructions with the AS method by comparing them with the SAS reconstructions by means of a colour scale.

Methods and materials

Sample

A collection of eight mandibles of children who died in the late 19th and early 20th centuries was used. The mandibles had been donated to science at the Institut d'Anatomie Normale, Strasbourg, France. According to French law, all research based on these elements of skeletons is exempt from any requirement to obtain the approval of an additional institutional review board for their use. The sample comprised five females and three males. The age-at-death ranged from 14 to 64 months. In total, there were 52 developing germs of permanent teeth: 24 incisors, 14 canines and 14 molars.

Data acquisition

Each mandible was scanned using a high-resolution peripheral micro-CT scanner (Xtreme CT; Scanco Medical, Brüttisellen, Switzerland) and two CBCT scanners (CBCT 9000 3D and CBCT 9500 3D; Carestream, Marne-la-Vallée, France). Isotropic spatial resolution was obtained with the three devices. Acquisition settings are presented in Table 1.

Data were exported in DICOM (Digital Imaging and Communications in Medicine) format and then converted to TIFF (Tagged Image File) format.

Table 1 Settings for micro-CT and CBCT acquisitions of the 52 developing germs: voxel size, FOV, tube voltage and tube current

Device	Voxel size (μm)	FOV (mm)	Tube voltage (kV)	Tube current (mA)
Xtreme CT (micro-CT)	41	126 × 155	60	1
Kodak CBCT 9000 3D	76	50 × 37	85	2
Kodak CBCT 9500 3D	200	90 × 150	90	10
	300	180 × 200		

FOV, field of view; kV, kilovolts; mA, milliamps.

Segmentation and 3D reconstruction

Two segmentation procedures were used in this study: The first—reference—segmentation was SAS, which has been described and validated in previous publications.^{26–29} The SAS of the tooth of interest was used with the AMIRA® software package (v. 5, <https://www.fei.com/software/amira-avizo/>). The SAS procedure was carried out by creating a label field and by using the tools “Magic Wand” and “Blowtool”, with manual adjustments. Teeth that required fully manual segmentation using editing tools were excluded from this study to minimize operator bias. Subsequently, the 3D triangle-based surface of each tooth was reconstructed from the data sets in polygon format without smoothing, to preserve the raw volume measurements.²⁶

The second—experimental—segmentation, *i.e.* AS, was used with the AVIZO software package (v. 8.1, <http://www.fei.com/software/avizo3d/>). The “watershed tool” for segmentation includes three steps (Figure 1). In the first step, two materials are created: “tooth”, which is the tooth of interest, and “background” or “outside”, which comprises the structures surrounding the tooth of interest. Two axial slides of the “background” without the tooth of interest were selected and marked as can be seen in Figure 1a,d. Next, two axial slides with “tooth” and “background” were selected and marked with the brush tool (Figure 1b,c). The labels were indicated at some distance from the boundaries.

In the second step, the Watershed Tool automatically segments all slides (axial, coronal and sagittal planes) and, in the third step, the 3D reconstruction is displayed (Figure 2). In the same way as for the SAS method, the 3D triangle-based surface of each tooth was reconstructed from the data sets in polygon format without smoothing to preserve the raw volume measurements.

The volume measured for the tooth of interest was recorded.

The volume measurements of the AS method group were compared with those of the SAS method group.

Statistical analysis

Reproducibility of measurements: Inter- and intra-examiner reliability was calculated with the intraclass correlation coefficient (ICC). To test the intra-examiner reproducibility, slice data were re-examined after an interval of 1 week. The test was performed on two different examiners: a dentist and a medical student.

Comparison of volumes

Data were analysed with the RStudio software (Version 1.0.44, rstudio.com). First, Pearson correlation analysis was performed to show the potential relationships between the volumetric measurements of the SAS and AS groups. Bland and Altman’s method³⁰ was used to assess the degree of agreement between SAS and AS. In this method, the difference between the measurements is plotted against their mean (which is considered to be the best estimate of the true values).

Regression analysis was performed according to the Passing Bablok method.³¹ If the 95% confidence interval (CI) of the slope of the relationship (slope *b*) between two measurements that were being compared included 1, and the 95% CI of the ordinate of the relationship at the origin (intercept *a*) included 0, no statistically significant difference was noted.³¹

Geometric discrepancies in visualization of distances within each pair of SAS and AS surfaces: To visualize the differences within each pair of SAS and AS 3D surfaces, surface registration was used to place the AS reconstruction in the same plane as those obtained by

Figure 1 Screenshots of the four-step labelling sequence for the AS method. AS, automatic segmentation.

Figure 2 Screenshot of the segmentation using Watershed method.

SAS. The distance between the two sets was minimized by using the iterated closest points algorithm.³² To evaluate the global error after registration, the mean square root was calculated.

A colour map created with AVISO® was used to display the topography of geometric discrepancies. The smallest and largest discrepancies were displayed on the map in blue and red, respectively. The upper and lower extremes of the colour map were the maximum and the minimum distances between the two reconstructions of each pair considered.

Results

Study sample

The sample consisted of 52 developing teeth: 12 central incisors, 12 lateral incisors, 14 canines and 14 molars. The two groups (SAS and AS) were composed of 52 volumetric measurements each.

Reproducibility of measurements

With the SAS group, the intra- and interexaminer reproducibility of 20 vol measurements was very high, with ICCs of 0.998 and 0.999, respectively.²⁷

With the AS group, intra- and interexaminer reproducibility of 20 volumetric measurements was also very high, with ICCs of 0.999 and 0.999, respectively.

Comparison of volumes

We found a strong correlation coefficient between the volumes in the SAS and AS groups for each voxel size: p -value < 0.0001 and Pearson correlation > 0.997.

Automatic segmentation with micro-CT

When the degree of agreement was compared using the Bland-Altman method, the sample was generally located between the upper and lower limits of agreement [mean ± 1.96 standard deviation (SD)] (Figure 3), indicating that the results of the two segmentation methods (SAS and AS) were not graphically different from each other. A slightly higher estimation was observed for volumetric measurements of the AS group compared with the reference SAS group.

With the Passing Bablok regression, no statistically significant difference was observed between SAS and AS volume measurements [Intercept $a = -0.362$; 95% CI (-2.875 to 3.309) and Slope $b = 1.001$; 95% CI (0.97 to 1.017).

Comparison between the reference semi-automatic micro-CT segmentation and CBCT automatic segmentation

With the Passing Bablok regression, the slope, b , was near 1, but the intercept, a , moved further away from the value 0 as the voxel size increased. Measurements

Figure 3 Bland and Altman plot of difference in tooth volumes between SAS and AS groups with micro-CT. Positive values indicate higher volumes calculated from AS than from SAS data. AS, automatic segmentation; SAS, semi-automatic segmentation.

were then correlated and differences between them were explored with the second Bland-Altman method. (Table 2)

The Bland-Altman method was used to compare the 41 μ m SAS data with successive 76, 200 and 300 μ mAS data (Table 3). The mean of the differences was lower than those obtained for the micro-CT and the standard deviations were higher, indicating that AS reduces the volume of the tooth, especially as the size of the voxel increases. The accuracy of the measurements was also lower for the AS on CBCT than on micro-CT.

Visualization of distances within each pair of SAS and AS surfaces

All micro-CT and CBCT reconstructions of the AS group were rigidly registered on the reference

reconstructions of the SAS group. Each pair represented a single tooth. For all 52 pairs of SAS and AS surfaces that were compared, the root mean square error (RMSE) was of the order of 0.04 mm (0.04 mm SD) when the distance between the SAS and AS surfaces of 41 μ m voxel size were compared. However, the RMSE increased with the voxel size when SA 41 μ m was successively compared with 76 μ m (mean RMSE = 0.20 mm; 0.11 mm SD), 200 μ m (mean RMSE = 0.29 mm; 0.11 mm SD) and 300 μ m (mean RMSE = 0.39 mm; 0.11 mm SD).

For the whole sample, the maximum differences, shown in red, were mainly located at the cervical margins, cusps and cracks. The histograms show the distribution of different discrepancies. This gives information on the maximum distance, and highlights segmentation problems such as over or under segmentation. (Figure 4).

Table 2 Bland and Altman plot of difference in tooth volumes between SAS and AS groups with micro-CT

micro-CT 41 μ m vs:	Intercept	Intercept 95% CI	Slope	Slope 95% CI
CBCT 76 μ m	-4.553	-8.709 to 0.307	-0.974	0.934 to 0.996
CBCT 200 μ m	-6.189	-9.270 to -3.651	-0.985	0.967 to 1.014
CBCT 300 μ m	-10.687	-10.885 to -7.114	-0.975	0.955 to 0.999

AS, automatic segmentation; CI, confidence interval; SAS, semi-automatic segmentation. Positive values indicate higher volumes calculated from AS than from SAS data.

Table 3 Bland and Altman plot of difference in tooth volumes between SAS and AS groups with micro-CT

Micro-CT 41 (μ m) vs:	Mean differences (mm^3)	Mean + 1.96 SD (mm^3)	Mean - 1.96 SD (mm^3)
CBCT 76	-9.95	9.9	-29.81
CBCT 200	-8.53	5.35	-22.4
CBCT 300	-13.91	0.91	-28.74

AS, automatic segmentation; SAS, semi-automatic segmentation. Positive values indicate higher volumes calculated from AS than from SAS data.

Figure 4 Visualization of differences between reconstructions from CBCT and micro-CT data aligned with rigid registration in Avizo. Two representative pairs of teeth are shown. From left to right: representation of CBCT AS reconstructions by using voxels of 41, 76, 200 and 300 μm . All reconstructions are registered against SAS micro-CT data at 41 μm . From top to bottom: cervical view of tooth 41 (specimen 202), vestibular view of tooth 46 (specimen 214). Colour maps (mm) are adjusted to minimum and maximum values observed. The colour map starts with blue (minimum distances), then passes through yellow, and ends with red (maximum distances). The histograms show the distribution of the discrepancies (To view this image in colour, please refer to the online version of this paper). AS, automatic segmentation; SAS, semi-automatic segmentation.

Discussion

In this study, the aims were (1) to assess the accuracy of volumetric measurements by comparing two segmentation methods and (2) to visualize the topography of the geometric differences in reconstructions with these two segmentation methods (SAS *vs* AS). The first interest of this work was that it compared this AS with a previously validated method (SAS method).^{17,27–29}

The validation of a method is based on its accuracy and precision. Accuracy is the validity of a value. Precision or reliability is the average deviation. These parameters are essential for dental research.^{33,34} Statistical results are important in assessing a method and the aim is to determine whether the method is repeatable and/or reproducible.³³

In our study, the reliability was tested with intraobserver reliability and interobserver reliability. In the work presented here, the interobserver reliability was tested on a dentist and a medical student. The latter was less experienced in tooth anatomy and its CT diagnosis. However, the reproducibility was very strong. Intraobserver precision was also very strong, which means that our method seems to be reliable and easy to use.

The accuracy or validity evaluated the closeness to the “ground truth” which, in our protocol, was the value from the SAS method validated in a previous study. Micro-CT AS volumes appeared to be slightly larger than SAS volumes. Bland and Altman evaluation showed that CBCT AS volumes were smaller than the reference micro-CT SAS volumes and SD was higher.

This can be explained by the watershed technique used to segment the labels. Once the interesting areas have been marked, watershed uses the grey scale of radio density to indicate relief. When the frontier between two labels has the same radio-opacity, the segmentation process can leak out of its boundaries (over segmentation).^{35,36} This problem has been seen in other AS work.^{2,16,36} The frontier or relief is more or less “flooded”. This could be a limitation of the AS method presented here when sharpness is not sufficient.

After alignment of AS and SAS teeth, the distance between the two reconstructions was evaluated. The maximum discrepancies were found at the cervical margins, and at the dental furrows and fissures caused by the process of dehydration post mortem. These locations were similar to those found in our previous study comparing the AS and SAS methods.³⁷ These parts covered zones where even manual segmentation was complex. The discrepancies were small on average (less than the voxel size of 46 μm). Our segmentation method used on CBCT led to under segmentation each time in the apical area and sometimes to over segmentation. These problems seem to stem from the CBCT image quality. The increase of the voxel size, the noise, the artefacts and the lack of contrast were the parameters of the image quality causing these segmentation problems. Defects of this kind have been observed with all AS techniques. The AS method seems to be suitable for volume measurements with CBCT acquisition in the research field but it seems to provide good AS results with micro-CT images. Bland and Altman results for CBCT show that the segmented volume is underestimated but

suitable for measurements because of the large standard deviation. Some tasks in dental practice do not necessarily need high accuracy but rather a general idea of the volume. In such cases, this method should be tested *in vivo*.

AS is a dynamic field of research. The limit between AS and SAS is blurred and depends on what we are looking for. “Fully automated segmentation” is difficult to obtain because there are many kinds of CBCT images. The differences lie in the voxel size, the dose of radiation and the signal/noise ratio. The images vary considerably and may need pre-processing before being used by automated segmentation software.^{2,23,36} Yanagisawa *et al* presented an image pre-processing method that normalized the brightness in the different tissues. Enamel, dentine and dental pulp tend to show dispersion of brightness values that complicates the segmentation.³⁶ Naumovich *et al* estimated that AS with watershed would require each object on the original image to be marked or labelled. This is what was done in our study but the question arises as to whether this technique can be considered as automated since we used four slices to mark each object.

Multitooth segmentation is possible for tooth crowns with our method. This type of segmentation enables several teeth to be segmented individually in a single segmentation session. It uses individual labelling that is similar to that described by Yanagisawa.³⁶ Another option is to perform pre-segmentation of the bone and teeth and then a second segmentation step for each individual tooth. In comparison with the study by Naumovich, our technique seems to offer better individualization of the tooth by using multilabelling rather than the cutting tool after labelling all the teeth together.²

Watershed is the common denomination for a multiplicity of processes that can be topographic, viscous, or stochastic. The contours may or may not be apparent, and may be defined on pictures where the nodes are weighted or on graphs where the edges are weighted.³⁵ In Avizo, the watershed uses a gradient magnitude image that is calculated with the Canny edge detection method, which provides a landscape image controlling the expansion of markers.

A problem of over and under segmentation can be observed in Figure 5. This is the main problem we encountered when using the watershed method on cone beam images. In these examinations, the image resolution did not enable clear boundaries to be obtained between the dentine, the periodontal ligament and the alveolar bone, and leaks inevitably occurred. It may be necessary to apply filters in the pre-processing before segmentation so as to obtain sharp limits. In this case, it would be interesting to check whether the filters led to a loss of information and, if so, to evaluate it.

In order to find the true distances between models, we did not apply smoothing and kept the voxel presentation of the reconstruction. In many studies, smoothing is applied and it thus becomes impossible to know

Figure 5 Over- and under-segmentation after AS on the same tooth (46 of specimen 211) with a voxel size of 76 μm . AS, automatic segmentation.

what kind of mapping was performed and whether it underestimated or over estimated the volume. In such cases it is difficult to work backwards and to compare volumes.^{2,16,24} (Figure 6).

Conclusion

In the present study, the AS method using watershed provided accurate and precise measurements of a germ from 3D micro-CT data that were similar to those of the SAS method. The topography of the geometric differences in a comparison between 3D micro-CT reconstructions with the AS method and with the SAS method was similar to that for SAS *vs* manual segmentation.

AS of a tooth is possible if the images coming from 3D acquisition are sufficiently sharp. Otherwise it is impossible to clearly distinguish the surrounding tissues from the tooth and the segmentation will be over extended. Image contrast and noise can be improved by filters. However, there is no universal filter; each needs setting adjustments. Moreover, even if the filters are edge preserving, there is loss of information. This and previous studies show that we use these AS

Figure 6 Tooth 46 (specimen 211) segmented with a smoothing filter on the left and tooth segmented without any filter, showing the interest of avoiding the use of a smoothing filter in the evaluation of an AS method. AS, automatic segmentation.

in the aim of improving measurements of volume or distance.

The other way of improving image quality is to enhance the 3D acquisition in order to record images that are sharper and thus easier to segment.

The current variability of images obtained from CBCT seems to mean that AS processing should not be used alone. A minimum of human intervention is necessary and two strategies are possible. A filter can be applied upstream to obtain an image that is sufficiently sharp for AS to function. In this case, statistical studies are needed to assess the impact of the filter on the volume measurements. Alternatively, AS can be used to accelerate the process so as to leave time for a phase of verification and manual modification of the segmentation.

In summary, the results of the study allow us to conclude on three points:

- Firstly, in the field of odontological research, images

of the dental organ derived from micro-CT can be segmented automatically using the watershed method presented for volume evaluation.

- Secondly, clinically, the method presented for AS of the teeth from CBCT images does not make it possible to obtain sufficiently precise volume measurements.
- Thirdly, the AS used with CBCT can nevertheless be used in clinical analyses to obtain the general form of the ROI.

Acknowledgments

This work was supported by Toulouse University Hospital (CHU de Toulouse), by Toulouse University (Université Paul Sabatier), the research platform of the Toulouse Dental Faculty (PLTRO). The authors thank Ms Susan Becker for her assistance with English language editing.

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