RESEARCH ARTICLE

Accuracy of software designed for automated localization of the inferior alveolar nerve canal on cone beam CT images

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Objectives: The aim of this study was to design and evaluate a new method for automated localization of the inferior alveolar nerve canal on CBCT images.

Methods: The proposed method is based on traversing both panoramic and cross-sectional slices. For the panoramic slices, morphological skeletonization is imposed, and a modified Hough transform is used while traversing the cross-sectional slices. A total of 40 CBCT images were randomly selected. Two experts twice located the inferior alveolar nerve canal during two examinations set 6 weeks apart. Agreement between experts was achieved, and the result of this manual technique was considered the gold standard for our study. The distances for the automated method and those determined using the gold standard method were calculated and recorded. The mean time required for the automated detection was also recorded.

Results: The average mean distance error from the baseline was 0.75 ± 0.34 mm. In all, 86% of the detected points had a mean error of <1 mm compared with those determined by the manual gold standard method.

Conclusions: The proposed method is far more accurate and faster than previous methods. It also provides more accuracy than human annotation within a shorter time.

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Introduction

There are risks of damaging the inferior alveolar nerve (IAN) during orthognathic surgery, implant placement, cyst removal and osteotomies that can yield serious complications.^{1,2} Damage to the mandibular nerve can cause pain or permanent loss of tactile sensation of the lower lip and chin.³ Therefore, accurate identification of the IAN is extremely

important before undertaking these procedures.⁴ For example, implant placement requires pre-operative evaluation that includes precise measurements of the location and size of IAN with an error of <1 – 2 mm.⁵

In a guideline provided by Juodzbalsys and Wang,⁶ periapical radiography, panoramic radiography, tomography, CT and CBCT are introduced as methods for localizing the canal. There are many shortcomings with conventional radiography (periapical and panoramic), such as lack of cross-sectional information and

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image distortion.^{4,6} CT scans were developed which could overcome these shortcomings. CBCT then became an alternative to conventional CT because of its affordability, reduced radiation dose per examination and high accuracy.^{6,7}

The structure of the IAN canal is not always well defined on CT images and may not be easily detected.⁴ Also, there is significant individual variation in the exact arrangement of this canal in the mandible.⁸ It is clear that manual detection of the canal depends on medical expertise and previous experience.⁵

There have been efforts to automate detection of the IAN canal on images (CT or CBCT). They can be categorized into semi-automated (for which user interaction is required) and automated. Table 1 summarizes the existing methods.^{1,2,4,7–16}

To the best of our knowledge, only three studies focused on CBCT data and presented a fully automated method as well.^{2,7,15} In one of these studies, Kainmueller *et al*⁷ (at the University Hospital, Cologne, Germany, in 2009) segmented the mandible using an active shape model (ASM), which is constructed from 106 clinical data sets. In this article, the canal is presented as a graph (a set of nodes and edges). The suggested algorithm is started by providing the initial position of the canal. In the next step, the algorithm tries to optimize (Dijkstra-based optimization method) the graph such that the graph travels through the “dark tunnel” in the image. The authors claimed that their method was able to detect the IAN with an average error of 1.0 ± 0.6 mm.

In the next study, Kroon¹⁵ compared Lucas–Kanade tracking, demon and B-spline registration, ASM and active appearance model (AAM) segmentation. He found that the modified ASM method used by Kainmueller *et al*⁷ and the improved AAM method used by Rueda *et al*¹³ were far more accurate for localizing the IAN canal. Although altering the ASM method by adding several post-processing methods [*e.g.* filtering to remove noise, three-dimensional (3D) snake optimization and fast marching] did not succeed in improving the accuracy,

improvement of the AAM method was a success. They reported a mean Euclidean distance to a human observer of around 1.88 mm, which is not as accurate as human annotation.

In another study, Moris *et al*² tried to track the canal in CBCT images using matching and multiple hypotheses methods. Their method started with detection of the mental and mandibular foramina by searching for high-contrast gaps in the mandible. They then tracked the path bidirectionally using a matching technique consisting of a template function that maps spatial coordinates. The authors reported that this method could detect the canal with an average error of 0.99 ± 1.13 mm.

Because of the importance of IAN canal detection and because few studies have been conducted on this subject, we also focused on finding a technique to localize the IAN. In the present study, we combined morphological skeletonization and a modified Hough transform to localize the IAN canal on CBCT images. We also introduced new criteria for evaluating the results of this method.

Methods and materials

Subjects

Using a random numbers table, 40 CBCT images were randomly selected from an archive of 500 previously acquired images at one of the 2 main private oral and maxillofacial radiology centres in Shiraz. The inclusion criteria for test images were medium field-of-view (FOV) CBCT images of patients who had been referred for evaluation of their mandibular third molar teeth. Exclusion criteria included images that were impossible to determine a gold standard manually because of the lack of visibility.

Each patient was positioned in the NewTom™ VGi CBCT machine (QR Srl, Verona, Italy) with the aid of a guide light. The Frankfort horizontal plane was parallel to the floor, and the mid-sagittal plane passed through the glabella. The examinations were performed

Table 1 Overview of existing methods for localizing the inferior alveolar nerve canal on CBCT images (ordered chronologically)

Method	Modality	Automated or semi-automated	Mean distance (mm)	SD (mm)	Number of data sets
Stein <i>et al</i> ⁹	CT	Semi-automated	–	–	5
Lobregt <i>et al</i> ¹⁰	CT	Semi-automated	–	–	–
Hanssen <i>et al</i> ¹¹	CBCT	Semi-automated	–	–	–
Kondo <i>et al</i> ¹²	CT	Semi-automated	0.69	0.76	1
Rueda <i>et al</i> ¹³	CT	Automated	3.4	1.11	62
Sothivirat and Narkbuakaew ⁴	CBCT	Semi-automated	–	–	1
Yau <i>et al</i> ¹⁴	CT	Semi-automated	–	–	–
Kainmueller <i>et al</i> ⁷	CBCT	Automated	1	0.60	106
Kim <i>et al</i> ¹	CT	Automated	0.73	0.69	10
Kroon ¹⁵	CBCT	Automated	1.88	1.05	13
Moris <i>et al</i> ²	CBCT	Automated	0.99	1.13	15
Lloréns <i>et al</i> ¹⁶	CT	Automated	0.14	0.02	20
Koningsveld ⁸	CT and CBCT	Semi-automated	–	–	3 CT and 5 CBCT

“Mean distance” represents the average distance error and “SD” represents the standard deviation. “–” is used when this information cannot be found or is overly dependent on the accuracy of the user’s input.

Figure 1 Generating panoramic view.

at 4.71 mA and 110 kVp, with an exposure time of 3.6 s. The FOV was 8×8 cm for all images.

The raw images from the CBCT scan were converted to digital information and communication in medicine v. 3 multfiles using NNT viewer software v. 2.21 (Quantitative Radiology, Verona, Italy). The digital information and communication in medicine images were then loaded into the designed software for localizing the mandibular canal manually and establishing the gold standard. In the next step, the proposed algorithm was used to locate the IAN canal on the same images. This study was performed in accordance with the Declaration of Helsinki.

Localizing the inferior alveolar nerve canal manually

Two maxillofacial radiologists were trained to locate the canal using a set of three CBCT images not included in this study. Working independently after calibration and using the software, each of the 2 experts located the landmarks twice in all 40 CBCT images during 2 examinations separated by an interval of 6 weeks. Based on the axial images, curved multiplanar reconstruction was performed, and both panoramic and cross-sectional views of the mandible were obtained. The centre of the mandibular canal was identified using a mouse-driven graphic cursor on the reformatted panoramic view. The radiologists were able to adjust the canal based on the axial and cross-sectional images. This method was introduced by Gerlach *et al*¹⁷ as being the best method for manually localizing the IAN canal. The data obtained were used for intra-observer and interobserver analysis. Although there were good intra-observer and interobserver correlations, we decided to reach between-experts agreement as a criterion against which we could base our comparison with the results of the automated method.

Proposed algorithm

The main difference between the IAN canal and other structures seen on the CBCT images is the difference in intensity. As previously mentioned, however, the CBCT images are noisy; so, it is difficult to use the intensity directly for IAN canal detection. Pre-processing techniques such as histogram equalization and filtering could be applied to the images to enhance the process. Although pre-processing techniques make the images clearer, they are still not satisfactory for the detection process.

For image processing, one approach to overcome the poor quality of the images is to use any prior information available about the problem. Therefore, certain information was considered for addressing the problem at hand.

- We are looking for an empty, connected pipe. The IAN canal is a connected pipe and is not viewed as separate parts.
- The IAN canal path is smooth, and its position could be specified with respect to the mandible.

We considered these two points and applied them to the proposed method.

If the FOV of input images is limited to the mandible, no user intervention is required and the system can select the region of interest (ROI) automatically. However, owing to data variability, we considered an optional tool for interfering in ROI selection and redundant data elimination in order to achieve both generality and speed.

Although it is possible to use 3D CBCT images, many image-processing tools are developed for two-dimensional (2D) image processing. Therefore, the proposed method uses 2D images. To use 3D information, however, two processing methods (morphological skeletonization and a modified Hough transform) were applied to the 2D images in two perpendicular planes. The method is thus based on traversing both panoramic and cross-sectional slices and extracting and fusing the points with similar features. The proposed method could be summarized as follows.

In the first step, panoramic data must be derived as described elsewhere^{4,12,14} (Figure 1). By applying the active contour technique on panoramic projections, the

Figure 2 Extraction of the jaw bone by imposing active contour method on the panoramic projection of the data.

Figure 3 Teeth removal *via* a quadratic curve.

mandibular bone is separated, and redundant points are removed (Figure 2). In addition, the teeth could be detached with the aid of a quadratic curve as a mask (Figure 3).

Morphological skeletonization is then imposed on the panoramic slices to extract the centre of the IAN canal. To enhance the poor contrast of CBCT data, appropriate pre-processing filters and methods (*e.g.* adaptive thresholding and histogram equalization) are used.^{18,19} The results are refined by removing incorrect points in consideration of the general anatomy of the canal, which is similar to a fourth-order polynomial function. For this purpose, all of the detected points are projected onto a plane. Then, using the linear least-squares method, $f(x)$ is fitted to the points.

$$f(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0$$

During the fitting process, the coefficients are limited to specific intervals that were chosen experimentally:

$$\begin{aligned} -60 < a_4 < -30, \quad -20 < a_3 < 20, \quad -10 < a_2 < 10, \\ -10 < a_1 < 10, \quad a_0 > 0. \end{aligned}$$

After $f(x)$ is determined, the points farther away than five pixels are removed.

While traversing the cross-sectional slices, the Hough transform is used to detect circles with different sizes that correspond to the tubular shape of the IAN

canal^{20,21} (Figure 4). Finally, the results of the two phases are aggregated (Figure 5). Figure 6 shows an overview of the proposed method.

Evaluation of the software

The accuracy of the segmentation of the IAN canal was assessed by measuring the average distance error, which is the average Euclidean distance between the centre point of the IAN canal segmented by our method and the centre point of the manually extracted canal on each slice for all of the data sets. The standard deviation (SD) of the distance error was also calculated.

To increase the value of the results and show the performance of the method, we introduced some new criteria. The first criterion is the percentage of the detected points that were <1 mm and <2 mm distant from the gold standard's nearest point. This criterion shows the accuracy of the algorithm for detecting the IAN canal points. That is, it shows the power of the method for selecting the exact IAN canal points. Although this criterion shows the accuracy of the method for detecting these points, the algorithm detects the IAN canal only in clear areas, simply dismissing the less clear regions as indecipherable. To show the performance of the method from this point of view, another criterion was introduced. The new criterion is the percentage of the gold standard points which in a distance of <1 mm and <2 mm a point is detected by the automated method. In this case, the method that detects only the clearly seen IAN canal and dismisses the other areas will have a lower percentage than those that consider both the clearly seen areas and the less clear ones.

Statistical analysis

All variables and measurements were entered into a spreadsheet in Excel[®] v. 12.0 (Microsoft, Redmond, WA) and analysed using IBM SPSS[®] Statistics for Windows, v. 20.0 (IBM Corporation, Armonk, NY; formerly SPSS Inc., Chicago, IL). Intraclass correlation coefficients were used to determine intra-observer and interobserver agreement. The average distance error between the manually detected IAN canal and the

Figure 4 Feature extraction from panoramic and cross-sectional slices (points: detected circles, line: aggregated results).

Figure 5 Final result.

automatically detected IAN canal was calculated with the Euclidean distance formula.

$$\text{Distance} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2},$$

where x_1 , y_1 and z_1 are the coordinates for manual detection, and x_2 , y_2 and z_2 are the coordinates for automated detection.

Results

Table 2 shows the mean distances and percentages of the detected points that satisfy the criteria of having a mean distance error of <1 mm and <2 mm, respectively, for some sample cases and standard deviation and average of 40 images. The percentages of the gold standard points detected by the automatic method using the same criteria are also reported. The required time is based on the use of an Intel® Core™ i7 (3.90 GHz) processor (Santa Clara, CA). A parallel processing method (single program, multiple data; SPMD) was used during the detection phases of the algorithm.

Discussion

This study was performed to assess the accuracy of new software that had been specifically designed for

automated detection of the IAN canal. The average mean distance error from the baseline was 0.75 ± 0.34 mm. Overall, 86% of the detected points had a mean error of <1 mm compared with that found by manual detection (gold standard). In a study by Gerlach et al,¹⁷ two independent observers located the mandibular canal using three methods. The best-performing method, which was combining panoramic reconstructions with cross-sections, had a mean interobserver variability of 1.3 mm (SD 0.384 mm). As the mean distance error for our automated method (0.75 ± 0.34 mm) was lower than the interobserver variability of Gerlach et al's¹⁷ study, it was considered acceptable. In regions where the canal was not detectable by the radiologists, the automated algorithm also was unable to find the canal. Furthermore, the points detected with greater error were close to the mental foramen and anterior loop of the canal.

Our results showed more accuracy with our proposed method than the accuracy in previous studies that presented a fully automated method and tested it on CBCT images. For example, in 2009, Kainmueller et al⁷ detected the mandibular canal with an average error of 1.0 ± 0.6 mm. They used a method that was based on a combined statistical shape model of the nerve and a Dijkstra-based optimization procedure. In 2011, Kroon¹⁵ studied CBCT data and designed a fully automated software for extracting the mandibular canal. He obtained an average mean distance error of 1.88 mm (SD 1.05 mm). Another fully automated method that was tested on CBCT data was suggested by Moris et al² in 2012. They used a matching technique consisting of a template function that maps spatial coordinates to a cost. They reported a mean error of 0.99 ± 1.13 mm. The greater accuracy of our method could be explained by the fact that we used two perpendicular 2D images and then fused the points, whereas the previously described methods used only one plane. Also, our method uses the continuity of the IAN canal and its approximate position.

Kim et al¹ used feature-enhancing panoramic volume rendering for automatic extraction of the IAN canal on CT data. They tested their method on 10 CT data sets

Figure 6 Overview of the proposed method. ROI, region of interest.

Table 2 Percentages of automated and gold standard detected points with <1 mm and <2 mm mean error, mean distance error and the time required for automated detection

<i>Data set</i>	<i>Percentage of detected points with <1 mm mean error</i>	<i>Percentage of detected points with <2 mm mean error</i>	<i>Percentage of gold standard points for which in a distance of <1 mm a point is detected by the automated method</i>	<i>Percentage of gold standard points for which in a distance of <2 mm a point is detected by the automated method</i>	<i>Mean distance error (mm)</i>	<i>Time required for automatic detection (s)</i>
1	84	89	91	93	0.73	21
2	90	95	84	92	0.55	21
3	87	90	96	98	1.4	19
4	84	90	95	97	0.62	20
5	78	89	86	92	1.4	22
6	96	99	95	98	0.35	17
7	89	94	85	92	0.71	16
8	88	96	88	94	0.55	22
9	72	78	88	90	0.78	19
10	84	91	87	91	0.73	24
Standard deviation	6.5	5.6	4.2	2.9	0.34	2.5
Average (of 40 images)	86%	91.6%	89.5%	94%	0.75	18

and reported a mean error of 0.73 ± 0.69 mm. In 2012, Lloréns et al¹⁶ tried to segment jaw tissues on dental 3D CT images using fuzzy connectedness and morphological processing. They tested their approach on 20 CT data sets and reported a mean error of 0.14 ± 0.02 mm for IAN detection. It is obvious that methods applied to CT images generally provide more accurate results. This is expected because CBCT images tend to have a lower signal-to-noise ratio⁸ as a direct result of the reduced amount of radiation that is used.²²

The average time required for automated detection of the IAN canal in our study was about 18 s. The average time required for manual detection of the canal was 41 s for Observer 1 and 43 s for Observer 2. Few of the other studies^{1,8} have reported the time required for automated detection of the canal, although Koningsveld⁸ reported a computation time of about 20 s.

For establishing the gold standard, 2 experts manually identified the canal in our 40 CBCT images at 2 separate sessions, ensuring the validity of the coordinates against our gold standard values. We asked them to use the cross-sections and panoramic reconstructions together, a method introduced as the best-method for localizing the IAN canal by Gerlach et al.¹⁷ They compared three tracing methods based on CBCT to determine the anatomical position of the mandibular canal. Method I was based on coronal views (cross-sections), Method II was based on panorama-like reconstructions and Method III was a combination of the two methods. When the two experts agreed, the result was considered the gold standard. Although the validity of the gold standard can significantly influence the results, the other similar studies did not explain the exact method they used to establish their gold standards.^{2,7,15}

Although the present study presents a valuable method for automated detection of the IAN canal on CBCT images, it has some limitations. First, we excluded images that were impossible to use manually to determine a gold standard because of the lack of visibility of the canal. Hence, we cannot generalize the findings. Also, all of the images of our study were prepared using a single CBCT machine, although Liang et al²³ showed that the image quality varies widely among CBCT machines, another possible reason that we cannot generalize the results of our study. The radiation dosage in CBCT is another limitation because it may limit implementation of this technique to special cases. According to the SEDENTEXCT guideline,²⁴ CBCT should not be used routinely for any third-molar pre-surgical assessments. The guideline also suggests the use of CBCT for implant treatment planning only if there is clinical doubt about the position of the mandibular canal.

Conclusions

We contend that this software is far more accurate and faster than those previously available. It also provides more accuracy than human annotation regarding interobserver distance within a shorter time.

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