Combined Layer-by-Layer Segmentation Level Set Model Applied to Dental CBCT Image Segmentation

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Abstract: Cone beam computed tomography (CBCT) image technology is widely used in the oral healthcare service industry to Detect the alignment, shape, position, and orientation of the patient's teeth, and tooth segmentation based on the level set model is an important step in the reconstruction and visualization of the tooth's three-dimensional structure. In response to the error accumulation problem that occurs in the conventional layer-by-layer segmentation level set model, this paper proposes a combined layer-by-layer segmentation level set model, which reduces the number of segmentation error transfers, and at the same time reduces the amount of segmentation error accumulation. Two consecutive sets of level set function iterations are designed to lead the curve from the inside of the tooth to the tooth edge and perform accurate tooth contour segmentation. The first set moves the curve from the inside of the tooth to the vicinity of the tooth contour to avoid over-segmentation, and the second set moves the curve from the vicinity of the tooth contour to the edge of the tooth contour for further optimization. Ten CBCT images were randomly selected to test this model, and the experiments showed that the combined layer-by-layer segmentation level-set model was superior to the conventional layer-by-layer segmentation level-set model, with the VOE value reduced by 12.44%, and the results of tooth segmentation were more accurate and better displayed; the time spent was shorter, but not significant; and good segmentation accuracy could be achieved for various classes of teeth.

Keywords: Combined layer-by-layer segmentation, Level set model, Tooth segmentation.

INTRODUCTION

Dentists must accurately determine the alignment, shape, position, and orientation of the crowns and roots before treating a patient. Cone beam computed tomography (CBCT) technology can simulate the anatomy of the patient's maxillofacial and dental structures with X-rays, and the patient is exposed to a lower dose of radiation than conventional CT (computed tomography) [1-4]. CBCT images are three-dimensional（3D） images with sub-millimeter resolution, and a CBCT image usually contains 28-32 teeth, so it would take a professional dentist several days to manually segment all tooth in a CBCT image with high precision [1-4]. Automatic or semi-automatic tooth segmentation algorithms can achieve high-precision tooth segmentation and 3D modeling in CBCT images in a short period of time, which is clinically important, and we hope to realize a class of CBCT tooth segmentation algorithms that can be used in the clinic.

1. DEVELOPMENT OF THE LEVEL SET MODEL

Segmentation models based on level set methods are characterized as knowledge-driven, and segmentation methods represented by deep learning methods have obvious data-driven features [5].

The level set model was firstly proposed by Osher and Sethian in 1987 [6], the early level set model was built by defining the curve as a function of one dimension higher, *i.e*., the level set function is a zero level contour, the two-dimensional curve motion will be transformed into a three-dimensional surface motion, *i.e*., the change of the curve at each moment can be utilized to the zero level of the three-dimensional surface to representation, realizing the concise expression of the complex topology change during the curve evolution process, as shown in Figure **1**.

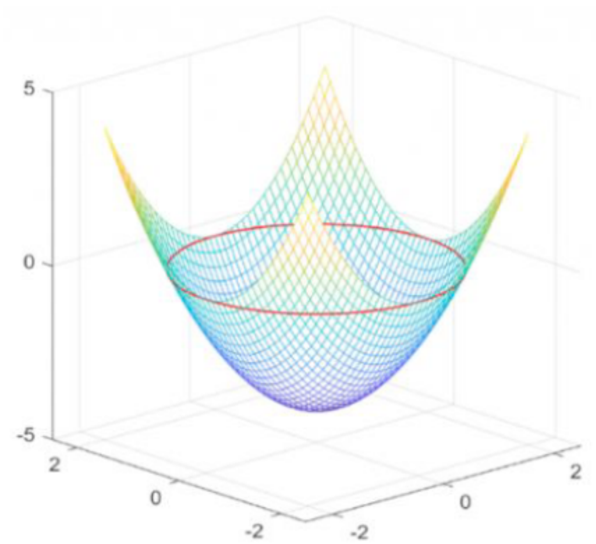

Figure 1: Diagram of level set method.

The geodesic level set model is a well-known level set model proposed by Caselles *et al*. in 1993 [7] and further refined and optimized by Caselles *et al*. in 1997 [8]. Edge-based level set models evolved from geodesic curve shifts assume that the edges between the foreground and background of the edge function

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are sufficiently distinct, but in the segmentation of medical images, the edges between the foreground and the background may be very blurred, which leads to the fact that this class of level set models cannot be directly applied.

In 1999 Chan and Vase proposed a level set model that does not require an edge function but only relies on area information, which is also known as Chan-Vase (CV) model [9]. If the gray values of the foreground and background regions of an image are close to each other or have discrete distributions, it is difficult for the CV model to achieve the desired segmentation effect.

For images with uneven distribution of gray values, Li *et al*. proposed a variable scale Region-Scalable Fitting Energy (RSF) [10], also known as level set model based on local region binary fitting, on the basis of the formulation of the energy generalization of CV models.

In order to guarantee the distance regularity of the level set function in the evolution process, Li *et al*. defined the regular energy term $\mathcal{R}(\phi)$, which applies the important property of the symbolic distance function $|\nabla\phi| = 1$ to the evolution process of the level set function [11] to guarantee the stable correspondence between the level set function and the curve, which can be referred to equation (1).

$$\mathcal{R}(\phi) = \int_{\Omega} p(|\nabla\phi|)dx \quad (1)$$

The regular energy term and the edge-based level set model together form the distance regularized level set evolution (DRLSE) model, which is defined as follows and can be referred to in equation (2).

$$\mathcal{E}_{DRLSE}(\phi) = \lambda\mathcal{L}(\phi) + \alpha\mathcal{A}(\phi) + \mu\mathcal{R}(\phi) \quad (2)$$

In the early research of tooth segmentation in CBCT images, Gao and Chae proposed a dual level set model [12] to segment multiple adjacent teeth in CBCT images. Since CBCT devices usually cannot recognize the demarcation lines of adjacent teeth, they refined this method by making reasonable use of the initialization required by the level set method, and defined a layer-by-layer level set method [13] for segmenting teeth in each cross-section of a CBCT image using a two-dimensional hybrid level set model.

Gan *et al.* [14] further refined the mixed level set model based on the same layer-by-layer segmentation by adding the internal and external energy terms of the RSF model, as well as a shape prior energy term [15], so that the segmentation of the current transect will asymptotically converge to the shape of the already segmented tooth region in its connected transects.

Ji *et al.* [16] defined a tooth thickness energy in a hybrid level set model and obtained better segmentation results on single root tooth segmentation; Xia *et al.* [17] extended the application of this method; Wang *et al.* [18] proposed a narrow-band implementation of the hybrid level set model; Gan *et al*. [19] redefined a new hybrid level set model by proposing a two-step segmentation method that first segments the upper and lower jaws and teeth, and then segments the teeth within them; Wang *et al.* [20] presented a fast and robust method for tooth crown segmentation. The above studies further advance the research on layer-by-layer segmentation and hybrid level set modeling.

2. TOOTH SEGMENTATION ALGORITHM BASED ON LAYER-BY-LAYER SEGMENTATION OF LEVEL SET MODEL

Most of the previous level-set methods for tooth segmentation in CBCT images are based on a layer-by-layer segmentation of the tooth section in each cross-section. This layer-by-layer segmentation method requires a high degree of consistency and clarity of the edges of each tooth in the cross section of the CBCT image. However, it is difficult to find such a layer of cross-section in the CBCT images of these patients in which the edges of each tooth are clear; in addition, the direction of the normal vector between the jawbone and the path of X-ray irradiation is not completely perpendicular to the patient's jawbone when the patient is photographed. The final result is that the layer-by-layer segmentation method can accurately segment only some of the CBCT images, it has a low clinical application value and cannot meet the demand for high-precision CBCT tooth segmentation algorithms in the oral healthcare industry.

It was found that by independently and accurately segmenting the boundaries between adjacent teeth, the conditions for the use of the layer-by-layer segmentation method can be reduced from acting on all teeth in the cross-section at the same time to acting only on each tooth in the image, thus realizing direct and high-precision segmentation of each single tooth. On the basis of simple manual initialization of a single tooth, it is clinically important to automatically segment that tooth with high accuracy to meet the needs of the oral health care service industry for tooth segmentation algorithms in CBCT images.

We define the space where the CBCT image $I(x, y, z)$ is located as $\Omega = \{\Omega_1, \Omega_2, \Omega_3, ..., \Omega_n\}$, where n is the total number of cross sections of the CBCT image, and Ω_i $(i = 1, 2, ..., n)$ is each subspace of the space Ω

representing the layer i cross sections of the CBCT image. In the layer-by-layer segmentation-based level-set models for tooth segmentation, these level-set models do not act directly on the space where the CBCT image is located, but instead perform a two-dimensional segmentation of the subspace Ω_i of Ω, *i.e*., the tooth cross sections in each cross section, so that the segmentation of a single tooth can be performed directly without the need to segment all the teeth in the cross section at the same time as shown in Figure **2**, where the blue contour is the manually initialized pixel , and the red contours are the segmentation result of the layer-by-layer segmentation-based level-set model of the tooth.

2.1. Idea of Layer-by-Layer Level Set Segmentation Methods

The middle part of the tooth, *i.e*., the neck, is only connected to the air or gingiva, and has a clear and continuous edge in the CBCT image, which is less difficult to segment. The crown and root portions of the tooth are more difficult to segment. In the root portion, the alveolar bone was directly connected to the tooth and the grayscale values were very close to each other, resulting in a blurred border between the two and an uneven distribution of grayscale values in each segment of the border in the CBCT images. In the crown portion of the tooth, although the demarcation line between the tooth and the air is obvious, the demarcation line between neighboring teeth appears to disappear. The segmentation of vanishing edges is a difficult problem in the field of image segmentation, and it is often necessary to realize the segmentation purpose by some indirect means, such as: segmenting all the teeth on the cross-section at the same time, or achieving the balance of the segmentation area of each tooth by competition at the vanishing edges, but these indirect means themselves introduce new segmentation risks.

The layer-by-layer segmentation approach is able to convert the problem of 3D segmentation of teeth in CBCT images into a simpler segmentation problem: 2D segmentation of tooth contours in a given cross-section of a CBCT image based on the given tooth contours in the neighboring cross-section. Considering that the shapes of teeth in adjacent cross-sections are roughly similar, the level set model is applied to initialize the level set function directly from the existing segmentation results of adjacent cross-sections in the process of 2D segmentation of a cross-section of a CBCT image.

In the layer-by-layer segmentation process, by default, the tooth segmentation results of neighboring cross-sections are accurate, and the changes of tooth contours between neighboring cross-sections, though small, still result in the accumulation of segmentation errors layer by layer. In the actual segmentation process, if the segmentation model pays too much attention to the tooth segmentation results of neighboring cross-sections and ignores the changes of tooth contours between neighboring cross-sections, the strong binding force will lead to over-segmentation or under-segmentation.

2.2. Combined Layer-by-Layer Segmentation

The problem of segmentation of tooth contour in the cross section is simplified on the basis of layer-by-layer segmentation, and the existing segmentation results of adjacent cross sections are first processed with morphological corrosion and thresholding to ensure as much as possible that the processed region is inside the tooth region in the current cross section, and then the level set function is initialized according to the processed region, which simplifies the process of curve evolution to the segmentation process from the inside of tooth contour to the edge of tooth contour.

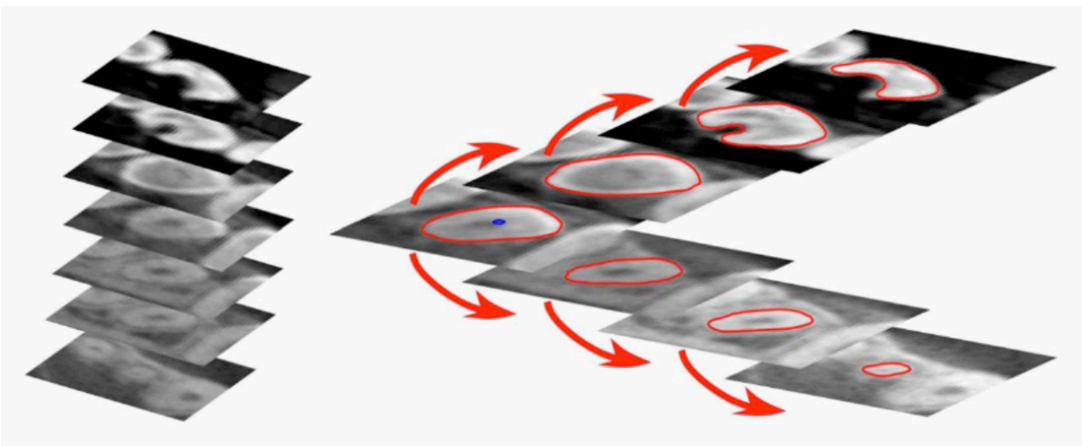

Figure 2: Segmentation process of the level set model for layer-by-layer segmentation of teeth in CBCT images.

To address the problem of error accumulation, we propose a combined layer-by-layer segmentation level set model. When segmenting a tooth in a cross-section, it is known that the segmentation result may have some segmentation error or some difference with the tooth contour in the current cross-section, in order to reduce the number of segmentation error transmission and reduce the number of accumulation of segmentation error, two successive iterations of the level set function are designed to lead the curve from the inside of the tooth to the edge of the tooth contour and to perform the accurate segmentation of the tooth contour. The first set of level set function iterations achieves an initial segmentation effect, moving the curve from the inside of the tooth to near the tooth contour and trying to avoid over-segmentation; the second set of level set function iterations achieves a more detailed segmentation effect, moving the curve that has already moved near the tooth contour further to the edge of the tooth contour. For the purpose of iteration of these two sets of level set functions, based on the DRLSE model, the level set function model for the first set of iterations is defined as follows, which can be referred to equations (3)-(6).

$$\mathcal{E}(\phi) = \mu\mathcal{R}(\phi) + \lambda\mathcal{L}(\phi) + \alpha\mathcal{A}(\phi) \quad (3)$$

$$\mathcal{R}(\phi) \triangleq \int_{\Omega} p_2(|\nabla\phi(x,y)|)dxdy \quad (4)$$

$$\mathcal{L}(\phi) \triangleq \int_{\Omega} g\,(x,y)H'(\phi(x,y))dxdy \quad (5)$$

$$\mathcal{A}(\phi) \triangleq \int_{\Omega} g(x,y)H(-\phi(x,y))dxdy \quad (6)$$

where $\mu > 0$, $\lambda > 0$ and $\alpha < 0$ are the coefficients of the energy terms $\mathcal{R}(\phi)$, $\mathcal{L}(\phi)$ and $\mathcal{A}(\phi)$, the level set function ϕ is defined on the two-dimensional subspace Ω_i of the three-dimensional space Ω, and (x, y) are the spatial coefficients in two dimensions. The energy term $\mathcal{R}(\phi)$ provides the regular force that allows the level set function to maintain the level set function sign distance regularity $|\nabla\phi| = 1$ during the iteration process, where the potential energy function $p_2(s) \geq 0$ at the time when $s = 0$ or $s = 1$, $p_2(s)$ reaches a minimum value of 0. The energy term $\mathcal{A}(\phi)$ provides a stabilizing dilatational force for the horizontal set function, and the energy term $\mathcal{L}(\phi)$ provides the smoothing force and edge attraction for the iteration of the level set function, where the attraction effect of edge attraction is related to the edge function $g\,(x, y)$, $g\,(x, y)$ is defined as follows and can be referred to equation (7).

$$g(x,y) = \begin{cases} 1 & \rho(x,y) \leq \theta \\ e^{-|\nabla I_i(x,y)|} & \rho(x,y) > \theta \end{cases} \quad (7)$$

where $I_i\,(x, y)$ is the cross-section of the CBCT image with the angle parameter $\theta \leq 90^{\circ}$ defined on the space Ω_i. $\rho\,(x, y)$ is the unit normal vector of the zero-level contour of the level set function $\vec{N}(\phi) = \nabla\phi/|\nabla\phi|$ with the angle between the gradient vector ∇I_i of the current cross-section, defined as follows, which can be found in equation (8).

$$\rho = \cos^{-1}\langle\vec{\mathcal{N}}(\phi)|\frac{\nabla I_i}{|\nabla I_i|}\rangle \quad (8)$$

The role and performance of both $\mathcal{L}(\phi)$ and $\mathcal{A}(\phi)$ depend on the marginal information in the marginal function $g\,(x, y)$, which $g\,(x, y)$ does not contain the edge information of the pulp and teeth. Although the grayscale values of pulp edges and tooth edges are comparable in the gradient modulus function $|\nabla I_i|$ of the cross-sectional image, it is still possible to distinguish the two on the basis of the difference in the orientation of the gradient vector ∇I_i of the cross-sectional image between the pulp edges and the tooth edges.

The gradient direction usually points from pixels with lower gray values to pixels with higher gray values. Since the grayscale value of the pulp is much lower than the grayscale value of the dentin region, the direction of the gradient at the edge of the pulp is usually directed from the center of the tooth contour to the periodontium. Also, since the gray value of the tooth is much higher than the gray value of the periodontal region, the direction of the gradient at the edge of the tooth usually points from the periodontal region to the tooth, opposite to the direction of the gradient at the edge of the pulp.

The direction of the normal vector of a curve expressed using a level set function, *i.e.*, the zero-level set contour of a level set function, usually points from the inside of the zero-level set contour to the outside of the zero level set contour. At the edge of the pulp, the direction of the normal vector of the curve is usually the same as the direction of the gradient of the cross-section image; at the edge of the tooth, the direction of the normal vector of the curve is usually opposite to the direction of the gradient of the cross-section image.

In order to lead the curve to the edge of the tooth contour and to maintain the smoothness of the edges of the level set function, the level set function model for the second set of iterations based on the DRLSE model is defined as follows, which can be referred to equation (9).

$$\mathcal{E}(\varphi) = \int_{\Omega_3} p(|\nabla\varphi_3(x,y,z)|)dxdydz + \int_{\Omega_3} g_3(x,y,z)\delta\big(\varphi_3(x,y,z)\big)|\nabla\varphi_3(x,y,z)|dxdydz \quad (9)$$

where the 3D edge function $g_3\,(x, y, z) = \exp\,(-\nabla(x, y))$. On the basis of initialization and layer-by-layer segmentation, further smoothing and optimization of the 3D edges of the tooth contour not only achieves the continuity and accuracy of the segmentation results in sub-pixel accuracy, but also better demonstrates the segmentation results.

3. RESULTS OF THE EXPERIMENT

In order to better test the performance of the combined layer-by-layer segmentation level set model proposed in this paper, 10 CBCT images were randomly selected from the dental CBCT image database of Shanghai Ninth People's Hospital, including a total of 274 teeth and 3200 different cross-sections, which had been prepared, calibrated and corrected in advance. These 10 CBCT images were taken in the same environment, using the same CBCT imaging equipment, model SS-X10010DPlus, from Hefei Meiya Optoelectronics Technology Co. The current of the X-ray emitter was between 9-10 mA and the voltage was between 80-90 KV. The imaging format of the CBCT images was the DICOM format, and the size of the stereo pixels was 0.25 mm^3, with an image size of 480 × 480 × 320 pixels. In these 10 CBCT images, the subjects had occlusal tablets in their mouths, the upper and lower teeth were clearly separated in the CBCT images, and the numbers of molars, premolars, canines, incisors, blocked teeth, and malocclusions were 65, 68, 37, 70, 14, and 19, respectively.

The segmentation results of adjacent cross-sections of a CBCT image, as shown in Figure **3**.

In order to evaluate the model proposed in this paper more accurately, the corresponding manual segmentation results are used as a reference standard. To evaluate the advantages and disadvantages of the model algorithm from the dimensions of segmentation accuracy and computing time, the Volumetric Overlap Error (VOE) [21] is used for the region-based accuracy

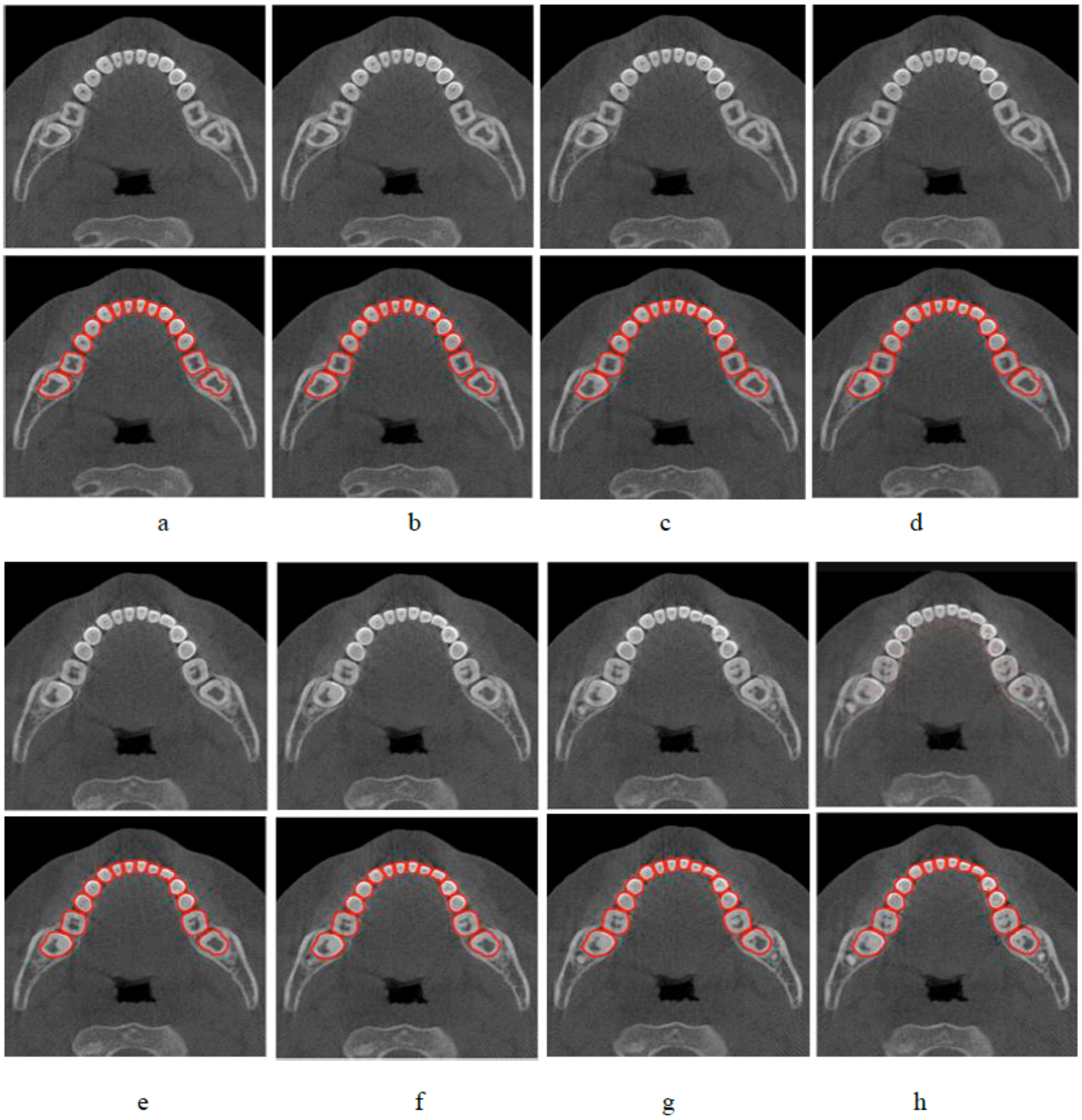

Figure 3: Dental contours of each cross-section during layer-by-layer segmentation.

Table 1: Quantitative Comparison of Segmentation Results between Combined Layer-by-Layer Segmentation Level Sets and Conventional Layer-by-Layer Segmentation Level Sets

Groups		1	2	3	4	5	6	7	8	9	10	Average Value	Standard Deviation
Combined layer-by-layer segmentation level sets	VOE/%	7.89	6.97	6.60	8.02	8.60	9.15	6.58	8.08	7.32	6.10	7.53	0.98
	computation time/s	15.18	14.69	14.34	14.82	14.99	15.30	15.40	14.56	14.26	14.56	14.81	0.40
Conventional layer-by-layer segmentation level sets	VOE/%	8.63	8.48	8.14	9.24	8.10	8.77	10.23	6.31	8.32	9.75	8.60	1.07
	computation time/s	15.40	15.23	14.43	14.33	14.86	15.30	14.88	15.29	14.28	14.23	14.82	0.47

characterization, and the VOE is defined as follows [22], which can be referred to equation (10).

$$VOE = 1 - \frac{|A \cap M|}{|A \cup M|} \quad (10)$$

Where A is the result of layer-by-layer segmentation of different level set algorithms, M is the result of manual segmentation and as an evaluation standard, the real overlap between the two is obtained by calculating the volume ratio of the intersection and concatenation of the results of different level set layer-by-layer segmentation algorithms and manual segmentation results, and the smaller the VOE, the higher the overlap between the results of layer-by-layer segmentation of the level set and the standard, *i.e*. the more accurate the segmentation results are. Taking the segmentation results of the teeth in 10 CBCT images manually segmented as the evaluation standard, the segmentation results of different level set model algorithms are compared quantitatively with the indexes, as shown in Table **1**, the combined layer-by-layer segmentation level set algorithm proposed in this paper has a significant increase in segmentation accuracy over the conventional layer-by-layer segmentation level set algorithm, and there is some increase in algorithmic efficiency as well.

The above experiments show that: the combined layer-by-layer segmentation level set model proposed in this paper is better than the conventional layer-by-layer segmentation level set model, with the average VOE reduced to 7.53%, which is 12.44% lower than the 8.60% of the comparison group, and the standard deviation of the VOE is 0.98, which is 8.41% lower than the 1.07 of the comparison group, and the results of tooth segmentation are more accurate and better presented; The time taken by the combined layer-by-layer segmentation level set model is 14.81 seconds, which is slightly shorter than the 14.82 seconds of the comparison group, but not significantly; the combined layer-by-layer segmentation level set model proposed in this paper is able to achieve good segmentation accuracy for various classes of teeth.

4. CONCLUSION

In this paper, a combined layer-by-layer segmentation level set model is proposed to improve the conventional layer-by-layer segmentation level set model, which achieves the optimization goal in segmenting various classes of teeth in CBCT images. This model is divided into two parts to segment the teeth in two consecutive groups, the former uses the layer-by-layer segmentation method to segment each cross-section in the CBCT image sequentially, and the latter further optimizes and smoothes the segmentation results of the obtained teeth to achieve higher precision segmentation results. This model contains two sets of level set function iterations, the first set of level set function evolution in which the level set function initialized inside the tooth contour is expanded until the curve is close to the edge of the tooth, and the second set of level set function iterations in which the curve is smoothly guided to the edge of the tooth, finally realizing the high-precision tooth contour segmentation.

The tooth segmentation level set model proposed in this paper requires manual initialization for localization, and due to the simple process of initialization and wide selection range, this process can be implemented by the deep learning method on behalf of the final realization of a fully automatic CBCT tooth segmentation algorithm.

CONFLICTS OF INTEREST

The authors report no conflict of interest, and this research received no specific grant from any funding agency.

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