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A level-set based approach for anterior teeth segmentation in cone beam computed tomography images

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ABSTRACT

Cone beam CT (CBCT) has gained popularity in dentistry for 3D imaging of the jaw bones and teeth due to its high resolution and relatively lower radiation exposure compared to multi-slice CT (MSCT). However, image segmentation of the tooth from CBCT is more complex than from MSCT due to lower bone signal-to-noise. This paper describes a level-set method to extract tooth shape from CBCT images of the head. We improve the variational level set framework with three novel energy terms: (1) dual intensity distribution models to represent the two regions inside and outside the tooth; (2) a robust shape prior to impose a shape constraint on the contour evolution; and (3) using the thickness of the tooth dentine wall as a constraint to avoid leakage and shrinkage problems in the segmentation process. The proposed method was compared with several existing methods and was shown to give improved segmentation accuracy.

1. Introduction

1.1. Motivation

The roots of teeth in the mouth are invisible to the naked eye since roots are buried within the jaw bones. Traditional dental X-rays provide a 2D uni-planar view of these roots of teeth. Unfortunately, these 2D views do not give an accurate spatial orientation of these roots in relation to neighboring structures. When teeth need to be moved in individuals who require orthodontic treatment to correct mal-aligned teeth, the accurate representation of the roots of teeth is critically important to ensure that teeth can be moved through bone and parked into pre-determined positions within the jaw bones before treatment commences. Hence, accurate segmentation of the 3D images of the jaw bones and tooth roots plays an important role in aiding clinical decision making through simulation of tooth movement. The use of multi-slice computed tomography (MSCT) to obtain 3D images of the jaws and teeth exposes patients to high amounts of ionizing radiation that pose a heightened risk of developing cancers [4–6]. In recent years, dental CBCT has gained popularity in dentistry for 3D imaging of the jaw bones and teeth due to its high resolution for bone tissues and relatively lower radiation exposure than MSCT [7]. However, tooth segmentation in CBCT is more challenging than that in MSCT because the image is noisier (Fig. 1), and the image contrast between the tooth root and the alveolar bone in CBCT is lower. The tooth boundary is too ambiguous to be exactly defined especially at the root. In clinical studies, tooth segmentation is usually performed manually by trained dentists, which is a very time consuming and tedious process. The availability of automatic or semiautomatic tooth segmentation methods will greatly assist the clinician in this task.

1.2. Related work

Several image segmentation algorithms have been proposed to segment objects from CT images. An adaptive thresholding method has been proposed by Heo and Chae [3] to segment the tooth. However, due to the nonhomogeneous intensity distribution inside each tooth, as well as the surrounding alveolar bones, thresholding usually leads to under segmentation or over segmentation problems.

Conventional active contour methods for medical image segmentation are either edge-based or region-based. Both methods have serious limitations. Edge-based segmentation methods, such as the active contour [8], use local edge information to evolve the contour to the edges. These methods fail at boundaries where the edges between the ROI and the background are not clear. Region

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Fig. 1. Image quality comparison between traditional MSCT and CBCT.

based segmentation methods [9], which use different intensity distributions of ROI and background to separate each other, fail in areas where the region inside the ROI has similar intensity levels to those of the background. Therefore, neither edge-based nor region-based methods are suitable for tooth segmentation in CBCT.

Hybrid segmentation methods [10] can overcome the limitations of the above methods by combining the intensity distribution and the edge information into one energy functional for optimization. However, without the aid of shape priors, such methods still fail to avoid the "shrinking" and "leaking" problems in areas where the ROI and the background have similar intensity distributions. 2D and 3D shape priors [11] have been developed for segmentation, but these methods are not suitable for shapes with large variations like human teeth. Building such shape priors requires large training sets and tedious training processes.

The distance regularized level set evolution (DRLSE) introduced in [13] was used by Barone et al. [14] to extract the root of the tooth from CBCT images. However, Barone et al. [14] failed to report the accuracy of segmentation and the results show that they can only segment a small portion of the root.

A recent tooth segmentation method using level set with shape and intensity prior has been proposed by Gao and Chae [1]. They propose to segment the crown and the root separately with two level-set based algorithms. This method generates a shape prior with intensity and boundary features and combines the three terms into one energy functional to be minimized. Although their method can segment the tooth crown in CBCT, it fails to segment the tooth root due to the following reasons. First, its calculation of intensity distribution is not accurate because the area inside the tooth contour actually consists of two different regions (the tooth dentine and the tooth pulp) and the area outside the tooth contour also consists of two different regions (the jaw bone and other soft tissues). Second, its shape prior is not robust. Third, it does not have any energy term to prevent leakage or shrinkage problems during the segmentation process. The disadvantages of Gao and Chae [1]'s method have been reported in [19].

1.3. Our approach

To address the problems in the segmentation of tooth roots in CBCT images, we propose to segment the tooth root in two steps: (1) segment the tooth pulp first instead of segmenting the tooth root directly and (2) segment the tooth dentine using the segmented tooth pulp to obtain a more accurate intensity density function of the tooth dentine and build a leakage-preventing energy term. The proposed method is novel in three aspects: we propose a more accurate dual intensity model, a novel shape prior term, and a new tooth dentine wall thickness constraint for preventing shrinkage and leakage.

1.4. Paper organization

Following the introduction, Section 2 describes the proposed algorithm. Section 3 presents the experiments and results, followed by the discussion in Section 4 and the conclusion in Section 5.

2. Proposed tooth segmentation approach

2.1. Crown segmentation

Segmentation of tooth crown is much less challenging than segmentation of tooth root, and crown segmentation has been well solved by Gao and Chae [1]. In this study, we use their algorithm to segment the crown from the adjacent teeth in CBCT images. We will not present the implementation of the coupled level set for crown segmentation, as the reader may easily refer to the article.

2.2. Root segmentation

Given a CBCT tooth image, our aim is to develop a semiautomated method that can define a contour separating the image into two groups: the tooth and the background. The method consists of two phases: image preprocessing and contour initialization, and tooth dentine contour evolution. The evolution of the tooth dentine contour is designed with five objectives:

- Penalizing energy: the contour is penalized with a signed distance function (SDF).
- Region energy (intensity distribution energy): we assume that the intensity distributions inside and outside the tooth follow different models. We propose a more accurate way to estimate the intensity distribution of the dentine.
- Edge energy: we define an external energy that can move the curve towards prominent edges of the object.
- Shape prior energy: we use the SDF of the final contour in the previous slice to serve as our shape prior [1].
- Dentine wall thickness energy: we use the interaction between the tooth pulp contour and the tooth dentine contour to prevent shrinkage and leakage.

2.3. Image preprocessing

The original CBCT images are first normalized to the intensity range from 0 to 255, followed by a filtering with a rotationally symmetric Gaussian filter of size 15×15 with standard deviation 1.5 to suppress noise (Fig. 2).