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Geometrical methods for level set based abdominal aortic aneurysm thrombus and outer wall 2D image segmentation

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ABSTRACT

Abdominal aortic aneurysm (AAA) is a localized dilatation of the aortic wall. Accurate measurements of its geometric characteristics are critical for a reliable estimate of AAA rupture risk. However, current imaging modalities do not provide sufficient contrast to distinguish thrombus from surrounding tissue thus making the task of segmentation quite challenging. The main objective of this paper is to address this problem and accurately extract the thrombus and outer wall boundaries from cross sections of a 3D AAA image data set (CTA). This is achieved by new geometrical methods applied to the boundary curves obtained by a Level Set Method (LSM). Such methods address the problem of leakage of a moving front into sectors of similar intensity and that of the presence of calcifications. The versatility of the methods is tested by creating artificial images which simulate the real cases. Segmentation quality is quantified by comparing the results with a manual segmentation of the slices of ten patient data sets. Sensitivity to the parameter settings and reproducibility are analyzed. This is the first work to our knowledge that utilizes the level set framework to extract both the thrombus and external AAA wall boundaries.

1. Introduction

The aorta is the largest artery in the human body and the main blood vessel leading away from the heart. An abdominal aortic aneurysm (AAA) is a permanent and irreversible localized dilatation of the abdominal section of this vessel. In clinical practice, diagnostic information of the 3D anatomy of an AAA is extracted non-invasively in vivo, through Computed Tomography Angiography (CTA). AAA can grow progressively larger and may eventually rupture if not diagnosed and treated. Accurate estimation of AAA rupture risk remains an open problem. Numerous risk indicators beyond the peak transverse diameter, which is not always reliable, such as wall stress, wall stiffness, intraluminal thrombus thickness and wall tension have been proposed (see e.g. [1]). To study these indicators and obtain a more reliable patient specific estimate of AAA rupture risk, accurate geometric characterization of the aneurysm is critical.

3D reconstruction of the complex anatomy of an AAA from medical imaging data can be achieved through either a slice-by-slice 2D segmentation of the structures of interest and the subsequent application of a 3D surface reconstruction method [2,3] on the extracted boundary points, or by utilization of a 3D segmentation approach that extracts the surfaces of interest in one step [4–7]. A manual 2D segmentation is a rather time-consuming procedure with the additional drawback of large intra- and inter-observer variability. An

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automatic segmentation method, which is both accurate and robust, would alleviate these problems. Level Set Methods (LSM's) [8,9] have been used in this direction due to their main advantages compared to other methods, such as the formulation of the level set without a parametrization resulting in a free transform and change of its topology, and the relative ease in extending the method to 3D problems. AAA segmentation is a challenging task for LSM's due to (a) poor contrast between thrombus and surrounding tissue that current imaging modalities produce and (b) strong edges that many neighboring structures present. Other issues that LSM's face are (a) the leakage of the advancing front into regions of similar intensity and (b) their high computational complexity which makes them slow. These issues explain why LSM's have been primarily used so far only for lumen and outer wall AAA segmentation. Examples of LSM application for AAA segmentation are the works by Loncaric et al. [10] and Subasic et al. [4] who implemented a 3D LSM for AAA and introduced a curve stopping criterion and the work by Magee et al. [5] which utilizes a 3D deformable model for an initial segmentation combined with an efficient level set implementation. Zhuge et al. [11] performed segmentation of the outer AAA wall in five steps: preprocessing, global region analysis, surface initialization, local feature analysis and level set segmentation and Sonka et al. [7] applied a novel 4D optimal border detection algorithm for automatic surface segmentation of AAA lumen. In the work of de Bruijne et al. [12] an interactive method for AAA sac segmentation is presented which relies on the fitting of a shape model to points with high correlation with the reference contour. The same group [13] also proposed a method based on Active Shape Models (ASMs) [14] for automated delineation of the outer aneurysm boundary in multiple MR sequences. Olabarriaga et al. [15] introduced a new method for deformable model-based segmentation of thrombus in AAA based on a 3D discrete deformable model (DM), Bodur et al. [16] presented an automatic segmentation of the aortic border by obtaining orthogonal to the centerline slices and using a novel variation of the isoperimetric algorithm which incorporates circular constraints and De Putter et al. [6] created an initial 3D active object from the lumen centerline which was then iteratively deformed via a time-discretized second order Newtonian-evolution equation to track the boundary. None, however, of these AAA segmentation methods is applied to track the thrombus-wall boundary. To our knowledge, the only work that presents a semi automatic method to extract the AAA wall thickness from CTA image data is that of Shum et al. [17] which does not, however, rely on the LSM but rather utilizes intensity histograms for the thrombus segmentation and a neural network for the outer wall segmentation.

The objective of the present work is to use the level set framework and introduce geometrical methods to generate a semi-automatic segmentation algorithm that accurately extracts the thrombus and outer wall boundaries from cross sections of 3D AAA image data. This is achieved by exploiting any available source of contrast at the thrombus-wall boundary including the presence of calcifications which appear in AAA CTA images as very high intensity regions and are commonly part of the wall. In cases where there is insufficient information at a region of the boundary to be exploited by the LSM, a method whereby wall thickness can be interpolated from neighboring regions is proposed. Two geometrical methods are presented to reconstruct the thrombus and wall boundaries exploiting the strong image features associated with the presence of calcifications. The proposed segmentation algorithm is applied to ten patient data sets (450 slices) and the extracted results are compared to a manual segmentation obtained from a medical expert.

2. Level set framework

2.1. *The main equations*

The application of the level set framework consists of two phases. In the first phase we use the FMM. In this method, the position of the expanding front is characterized by computing the arrival time $T(x, y)$ of the front as it crosses each point (x, y) [8]. If Γ is the initial location of the interface then $T=0$ on Γ. At time t the moving front is given by

$$\Gamma(t) = \{(x, y) \in \mathbb{R}^2 | T(x, y) = t\}. \tag{1}$$

The front is moving with a speed function in the normal direction $g_I > 0$, so the equation for the arrival function $T(x, y)$ is

$$g_I |\nabla T| = 1. \tag{2}$$

Here, the proposed edge-indicator function, which restrains the evolving front from leaking out of the desired region is

$$g_I(x, y) = \frac{1}{1 + \lambda \left| \nabla G_s * I(x, y) \right|^2}. \tag{3}$$

I is the image intensity and for $\alpha \in \mathbb{R}^2$, $G_s(\alpha)$ is the Gaussian with width s,

$$G_s(\alpha) = \frac{1}{4\pi s} e^{-(|\alpha|^2/4s)}, \tag{4}$$

which is used to reduce possible noise effects in the image. λ is a positive parameter. g_I is close to unity away from the boundaries and drops to zero near sharp changes in the image gradient. These changes presumably correspond to the edges of the desired shape. Efficient numerical schemes (upwind differencing) can be used to solve Eq. (2) (see [8]).

In the second phase we embed the initial position of the front as the zero level set of a higher-dimensional function ϕ and we link the evolution of this function to the propagation of the front itself through a time-dependent initial value problem. At any time, the front is given by the zero level set of the time-dependent level set function ϕ. So, at time $t \geq 0$, the front is

$$\Gamma(t) = \{(x, y) \in \mathbb{R}^2 | \phi(x, y, t) = 0\}, \tag{5}$$

where $\phi(x, y, 0)$ is the result of the FMM. The level set equation used in this phase is

$$\phi_t = g_I(x, y)(\kappa - c)|\nabla\phi| + \nabla\phi \cdot \nabla P. \tag{6}$$