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A semi-automated method for measuring the evolution of both lumen area and blood flow in carotid from Phase Contrast MRI

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ABSTRACT

Phase-Contrast (PC) velocimetry Magnetic Resonance Imaging (MRI) is a useful modality to explore cardiovascular pathologies, but requires the automatic segmentation of vessels and the measurement of both lumen area and blood flow evolutions. In this paper, we propose a semi-automated method for extracting lumen boundaries of the carotid artery and compute both lumen area and blood flow evolutions over the cardiac cycle. This method uses narrow band region-based active contours in order to correctly capture the lumen boundary without being corrupted by surrounding structures. This approach is compared to traditional edge-based active contours, considered in related works, which significantly underestimate lumen area and blood flow. Experiments are performed using both a sequence of a homemade phantom and sequences of 20 real carotids, including a comparison with manual segmentation performed by a radiologist expert. Results obtained on *the* phantom sequence show that the edge-based approach leads to an underestimate of carotid lumen area and related flows of respectively 18.68% and 4.95%. This appears significantly larger than weak errors obtained using the region-based approach (respectively 2.73% and 1.23%). Benefits appear even better on the real sequences. The edge-based approach leads to underestimates of 40.88% for areas and 13.39% for blood flows, compared to limited errors of 7.41% and 4.6% with our method. Experiments also illustrate the high variability and therefore the lack of reliability of manual segmentation.

1. Introduction

Cardiovascular diseases remain an important cause of death. Several imaging modalities are available to explore cardiovascular pathologies: angiography, Doppler echo, Computed Tomography and Magnetic Resonance Imaging (MRI). Clinical cardiovascular MRI has evolved from a modality that provided anatomic imaging to one that gives access, in a day-to-day practice, to functional information as well [1]. A key component of this enhanced utility has been the capability, with Phase-Contrast velocimetry MRI to analyze and quantify hemodynamic parameters. Phase-Contrast velocimetry MRI provides not only anatomical information on vessels but also functional information related to blood flow over the cardiac cycle. Fig. 1A reports an example of anatomical information (anatomical image), together with functional information (phase image). The evolution of blood flow through carotid is measured over a cardiac cycle using the intensity provided by phase image.

A major strength of MRI, compared to other modalities such as Doppler echo, regards its ability to give access to all anatomical regions in all orientations and its sensitivity to a broad range of flow velocities. This technique has a variety of clinical applications [1], including evaluation of valvular heart diseases (regurgitation and stenosis), assessment of left and right ventricular stroke volume, assessment of vascular stenosis [2], evaluation of arterial wall shear stress [3].

For a clinical use, analysis of the Phase-Contrast velocimetry MRI data requires the delineation of vessel lumen over the sequence, from which measurements, such as flow calculations, can be performed. The purpose of this work is to automate the delineation of carotid over entire PC-MRI sequences, in order to measure the evolution of both the lumen area and the blood flow over a cardiac cycle, and could be extended to additional measurements such distensibility for instance. Our proposal concerns a semi-automated analysis method. Manual interaction only regards the initialization of the automated analysis, compared to a fully manual analysis involving the manual delineation of vessel lumen over each image of an entire sequence, this being a tedious and time consuming task, non-compliant with clinical routine.

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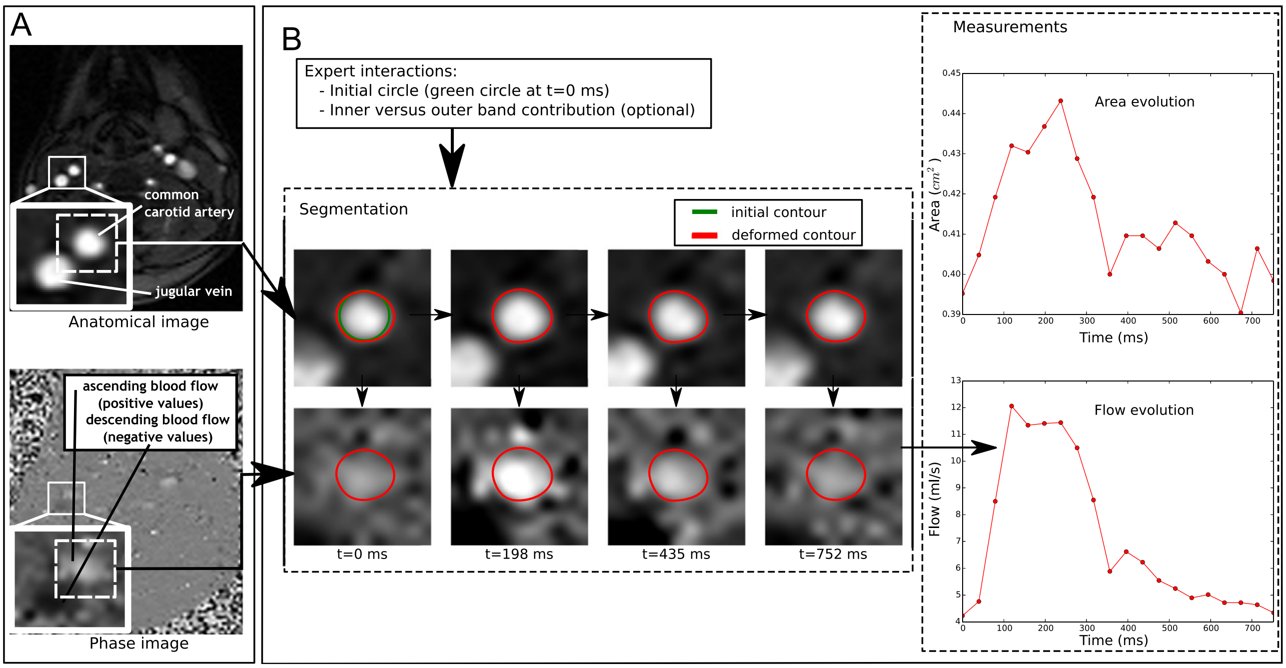

Fig. 1. Images (A) and principle of the proposed semi-automated analysis method (B). (A) Anatomical image (top) and phase image (bottom) from 2D cine PC-MRI for the examination of carotid. (B) Principle of the proposed approach including segmentation and measurements (curves on the right side). Area evolution. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Carotid lumen segmentation has been widely studied but not in the context of PC-MRI. Related studies have concerned 3D CTA (Computer Tomography Angiography) and MRA (Magnetic Resonance Angiography) [4–6]. Some of related methods are based on region-growing, active contours and vessels' centerline prior detection.

Recent studies involving PC-MRI sequences focus on large vessels differing from carotid, being a smaller structure. Considered larger structures belong to the thoracic area (e.g. aorta [7–10] and pulmonary artery [10]). The study related to [9] focuses on the aorta, using manually initialized edge-based deformable models applied to the anatomical image, without any blood flow measurement. 3D PC-MRI sequences are considered in [8], where vessels are semi-automatically segmented using phase images only, by coupling anisotropic filtering (for noise reduction) and edge-based deformable models (level-sets). In [10], vessel lumen is segmented using 3D Angiographic MRI images, and PC-MRI sequences are only used for computing velocity profiles. In [7], segmentation exploits phase information only, using edge-based active surfaces, where edge regards the frontier between the blood flow region and stationary tissues.

These previous works focus on 3D segmentation (except [9]), with underlying difficulty of extracting entire 3D structures depicting bifurcations for instance. Our context differs for these works because one focuses lumen area and blood flow evolution from a single 2D vessel slice from PC-MRI sequences. Besides, compared to previous works dealing with PC-MRI, one focuses on the carotid, being a smaller structure (e.g. diameter of about 25 mm for the aorta, against 7 mm for the carotid [11]). To our knowledge, except preliminary results limited to a single sequence [12], such an application of PC-MRI has not been considered yet.

In this work, we propose to segment the carotid lumen using narrow band region-based active contours: deformation is guided by statistics locally computed within bands surrounding the contour. As studied in this paper, this choice is motivated by the lack of contrast of carotid vessels, making edge-based approach unappropriate (compared to previously mentioned studies on PC-MRI sequences focusing on larger structures [7–10]). Note that such local region-based approaches have been widely studied for general purpose segmentation [13–15] as well as in previously mentioned works on 3D CTA and MRA images [4–6,16].

The main contribution of this paper concerns the proposed semi-automated analysis method for measuring both lumen area and blood flow, using, for the segmentation step, narrow band region-based explicit active contours inspired from [16]. Another part of the contribution regards the comparison performed with traditional edge-based active contours, as considered in the similar work (i.e. PC-MRI sequence analysis) focusing on the aorta [9]. This shows the need of a region-based approach for this anatomical structure. The last part of the contribution regards experiments involving both sequences of healthy volunteers and a sequence acquired using a carotid phantom. The use of a phantom is known to be relevant to evaluate segmentation algorithms for medical applications, compared to validation protocols limited to the use of reference segmentations resulting from manual drawings achieved by radiologist experts, with underlying uncertainty [17].

Section 2 describes the proposed semi-automated method, while Section 3 presents experiments and results. Before concluding, Section 4 discusses this work and related results.

2. Method

2.1. Overview

Fig. 1 A shows an acquisition example at a specific instant of an entire sequence (both anatomical and phase images are reported). Concerning the acquisition protocol, the axial slice is assumed to be manually selected (before acquiring an entire sequence) to be perpendicular to the common carotid artery (flow is maximal for a perpendicular plane): the axial plane is selected by the radiologist on a coronal plane of the carotid.

Fig. 1 B provides an overview of the proposed semi-automated analysis method. The input is the sequence of both anatomical and phase images. Segmentation is performed using anatomical