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Automated segmentation of the atrial region and fossa ovalis towards computer-aided planning of inter-atrial wall interventions

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ABSTRACT

Background and objective: Image-fusion strategies have been applied to improve inter-atrial septal (IAS) wall minimally-invasive interventions. Hereto, several landmarks are initially identified on richly-detailed datasets throughout the planning stage and then combined with intra-operative images, enhancing the relevant structures and easing the procedure. Nevertheless, such planning is still performed manually, which is time-consuming and not necessarily reproducible, hampering its regular application. In this article, we present a novel automatic strategy to segment the atrial region (left/right atrium and aortic tract) and the fossa ovalis (FO).
Methods: The method starts by initializing multiple 3D contours based on an atlas-based approach with global transforms only and refining them to the desired anatomy using a competitive segmentation strategy. The obtained contours are then applied to estimate the FO by evaluating both IAS wall thickness and the expected FO spatial location.
Results: The proposed method was evaluated in 41 computed tomography datasets, by comparing the atrial region segmentation and FO estimation results against manually delineated contours. The automatic segmentation method presented a performance similar to the state-of-the-art techniques and a high feasibility, failing only in the segmentation of one aortic tract and of one right atrium. The FO estimation method presented an acceptable result in all the patients with a performance comparable to the inter-observer variability. Moreover, it was faster and fully user-interaction free.
Conclusions: Hence, the proposed method proved to be feasible to automatically segment the anatomical models for the planning of IAS wall interventions, making it exceptionally attractive for use in the clinical practice.

1. Introduction

Anatomically, the atria are complex cardiac chambers with high variability between subjects [1, 2]. Although their body is typically described as simple concave shapes in normal cases [3], atrial enlargement of one chamber is common, negatively affecting the other chamber and changing their anatomies [4]. Moreover, high spatial and shape variations are frequently found in their connected structures (i.e. pulmonary veins - PV, vena cava -VC and appendages) and even in specific anatomical regions (e.g. fossa ovalis - FO) [1–3,5]. Due to all these reasons, minimally invasive atrial interventions are difficult, requiring multiple imaging modalities for planning (mainly computed tomography - CT) and guidance (e.g. ultrasound) [6,7]. Firstly, during the planning stage, the clinician visually evaluates the richly detailed images, searching for anatomical variations. Next, throughout the intervention, real-time images are used to guide the different instruments inside the human body until the target positions [7].

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Traditionally, both planning and interventional data are independently evaluated in a manual manner, being subsequently mentally combined by the expert throughout the intervention [7]. Nevertheless, such approach requires great experience, is very time-consuming, and frequently results in procedural failures and complications [7,8]. Thus, automated image-fusion strategies were proposed [9,10]. Usually, these strategies start with a segmentation of the target structures, being subsequently fused with the intra-procedural data [9]. As a result, the high-detail of the pre-operative stage is transferred to the intervention, enhancing and improving intra-procedural images [7,9].

The success of the aforementioned image-fusion strategies is directly related to the accuracy of the image alignment approach [7]. While some researchers focused on strategies to align the pre- and intra-procedural data using 2D/3D alignment approaches [10], landmark identification [11] and/or image registration [12], other researchers optimized the planning stages suggesting automated algorithm versions [2,13]. These automated methods showed a performance comparable to the manual analysis [2,14,15], requiring none or little user input, removing or minimizing the variability between observers and reducing the time spent during the planning [2]. Specifically for cardiac applications, atlas-based [16,17], deformable models [14,18] and machine learning strategies [15] were proposed to segment the different cardiac chambers. Particularly, the methodologies described by Ecabert et al. [14] and Zheng et al. [15] successfully segmented the four cardiac chambers plus the attached great vessels, and the atlas-based methodology from Kirisli et al. [16] proved its added-value for cardiac chamber segmentation in large databases of contrast-enhanced [16] and non-contrast-enhanced CT images [19]. However, these solutions still present inaccurate results in the thin mid-walls, showing overlapping regions [16] or merging of different contours [14]. As such, we recently proposed a competitive deformable model strategy to segment the atrial region (i.e. atrial bodies and aortic tract - AO) with a correct delineation of the mid atrial walls [18]. Such formulation allowed correct evaluation of the inter-atrial septal (IAS) wall, allowing its application for IAS interventions (e.g. transseptal puncture or atrial septal defect closure) and even improving the planning of multiple minimally invasive atrial interventions (e.g. atrial fibrillation, atrial appendage closure) [5,20]. However, a semi-automatic version was described in [18], requiring an initialization of each chamber. Moreover, specific landmarks/regions inside the inter-atrial wall, such as FO [5], were not detected.

The fossa ovalis is the thinnest region of the IAS wall, presenting an oval or circular shape and usually located posteriorly, at the junction of the mid and lower third of the right atrium (RA) [6]. It is described as a depression, composed by a thin flap (floor of the FO) and its surrounding margins designated as FO limbus [21]. Since direct physical access to the left atrium (LA) is not possible, the FO is used as an access point between the RA and LA [5,6]. This technique is termed transseptal puncture, which consists of a needle that is inserted percutaneously until the RA, puncturing the FO and accessing the LA [6]. The correct identification of the FO is crucial to identify the optimal access route between both atria [11], preventing complications, or multiple puncture attempts [5]. Moreover, the FO identification is also relevant in other LA interventions, namely for device selection and optimal route identification for catheter ablation, mitral valve (MV) replacement and left atrial appendage (LAA) occlusion [5,20,21]. Some researchers have investigated the added-value of the FO identification in a pre-interventional stage, proving that it eases the real intervention, especially for challenging anatomies [9,22,23]. Nonetheless, its identification is still performed manually [9,22], hampering its application in the clinical practice.

To overcome the aforementioned difficulties, a fully automatic segmentation strategy is proposed in this article to generate the

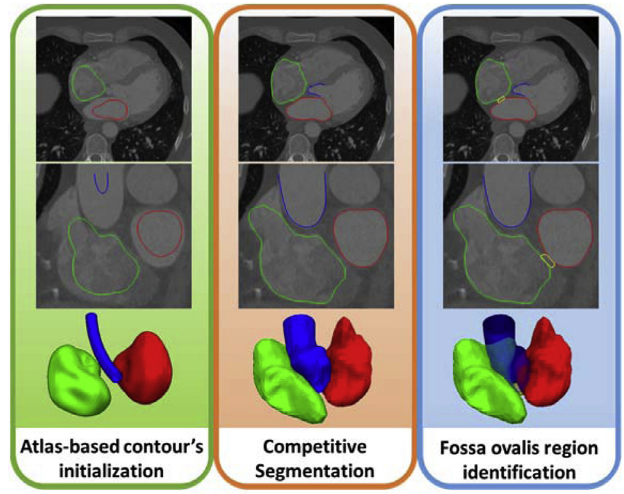

Fig. 1. Overview of the proposed fully automatic method for atrial region segmentation (red: LA, green: RA, blue: AO) and fossa ovalis identification (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atrial region models and the FO in CT datasets. Both models can improve the current IAS interventional planning, making it faster, more reproducible and simpler. The method starts by segmenting the relevant cardiac chambers (i.e. atrial region) around the IAS wall, allowing an accurate evaluation of wall thickness and shape. The proposed segmentation method is an extension of [18], with a robust initialization through an atlas-based technique. Then, since a correct representation of the IAS wall is used, the FO region is identified by assessing the intermediate mid wall positions of all contour pairs and spatial location information.

Overall, this work introduces three novelties: 1) extension of our previously presented atrial segmentation method with a fully automatic one; 2) a novel methodology to accurately segment the FO; 3) a clinical validation of the proposed method.

This article is structured as follows. In Section 2, a technical description of the proposed fully automatic atrial segmentation method is presented. In Section 3, the validation experiments and their results are presented. Section 4 discusses the performance of the proposed method against the state-of-the-art and expected inter-/intra-observer variability. Finally, the conclusions of this study are presented in Section 5.

2. Methods

The proposed fully automatic method comprises three sequential conceptual blocks (Fig. 1): 1) automatic and rough identification of the cardiac chambers through an atlas-based technique with global transformation models; 2) refinement of the target region boundaries using a competitive segmentation methodology that guarantees the integrity of the mid thin walls; and 3) identification of the FO region through the combination of the patient-specific wall thickness information (extracted from the anatomical models obtained in (2)) and a set of known anatomical references that provides the spatial location.

2.1. Atlas based contour's initialization

Due to the high feasibility previously demonstrated by atlas-based techniques [16], a similar methodology was selected to initialize our method. The traditional formulation finds the optimal transformation that aligns the target image with a labelled dataset (designated as atlas), subsequently applying it to the labels and