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Image registration and atlas-based segmentation of cardiac outflow velocity profiles

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ABSTRACT

Cardiovascular disease is the leading cause of death worldwide and for this reason computer-based diagnosis of cardiac diseases is a very important task. In this article, a method for segmentation of aortic outflow velocity profiles from cardiac Doppler ultrasound images is presented. The proposed method is based on the statistical image atlas derived from ultrasound images of healthy volunteers. The ultrasound image segmentation is done by registration of the input image to the atlas, followed by a propagation of the segmentation result from the atlas onto the input image. In the registration process, the normalized mutual information is used as an image similarity measure, while optimization is performed using a multiresolution gradient ascent method. The registration method is evaluated using an in-silico phantom, real data from 30 volunteers, and an inverse consistency test. The segmentation method is evaluated using 59 images from healthy volunteers and 89 images from patients, and using cardiac parameters extracted from the segmented image. Experimental validation is conducted using a set of healthy volunteers and patients and has shown excellent results. Cardiac parameter segmentation evaluation showed that the variability of the automated segmentation relative to the manual is comparable to the intra-observer variability. The proposed method is useful for computer aided diagnosis and extraction of cardiac parameters.

1. Introduction

At the beginning of the 20th century, cardiovascular disease was responsible for fewer than 10% of all deaths worldwide. Today, that figure is about 30%, with 80% of the burden now occurring in developing countries [1]. In 2001, cardiovascular disease was the leading cause of death worldwide [1]. In United States, coronary heart disease caused 1 of every 5 deaths in 2004 [2]. Therefore, one can conclude that diagnosis of coronary heart disease is a very important medical task.

In everyday clinical practice, a detailed analysis of Doppler echocardiography traces is often limited by a high frequency workflow in the echocardiographic laboratory. Currently, basic measurements of aortic outflow Doppler traces are routinely obtained by manual tracking of Doppler traces, predominantly providing data on valvular flows. Manual tracking of the traces is often cumbersome, time-consuming and dependent on the expertise of the cardiologist/sonographer. However, automatic trace delineation should reduce the required time needed for data analysis, while not increasing the measurement error. Previous clinical studies have demonstrated

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that additional data obtained by automatic trace analysis would provide relevant clinical data on left ventricular function, aiding in diagnostics and further patient management strategies [3,4]. Continuous wave Doppler outflow traces are mainly used to assess a potential pressure gradient across the aortic valve resulting from a narrowing of the valve. It was also shown that severe aortic stenosis shows not only higher but often also prolonged outflow velocities [5]. The detection of changes in myocardial contractility in the setting of coronary artery disease is an important diagnostic task. Besides a decrease in global systolic function, as detected by ejection fraction, and changes in regional deformation [6], it was suggested, from isolated myocytes research, that chronic ischemia decreases but prolongs contraction [7]. These observations show that the profile of the aortic outflow velocities might provide information on global myocardial function [8].

Ultrasonic imaging is a non-invasive medical imaging modality, which is routinely used in hospitals for the examination of cardiac patients [9]. Doppler ultrasound imaging provides useful information about blood velocities through the cardiac valves [10]. By measuring these velocities, clinical information on left ventricular (LV) inflow (mitral valve) and outflow (aortic valve) can be quantified, which is clinically useful to assess hemodynamic parameters and ventricular function. The interpretation of Doppler echocardiography data requires an integration of various hemodynamic measurements that can be obtained from the shape of the cardiac outflow velocity profile. To extract the information from the cardiac outflow velocity profiles acquired by the Doppler ultrasound, image segmentation and quantification of the segmented profiles is required. Both segmentation and quantification are usually done manually by expert cardiologist. However, manual segmentation of the images is usually a time consuming and tedious task. Cardiac Doppler ultrasound images are not exception from that. Since automating the segmentation and parameter quantification procedure has great potential for reducing the time cardiologist needs to spend to analyse each of the images, a new method for registration of aortic outflow velocity profiles is developed and presented in this paper. Within the registration procedure, a geometric transformation function is described which is specially developed for this type of the images. Also, a new atlas-based segmentation method is proposed, for automatic segmentation of cardiac outflow velocity profiles.

The atlas-based segmentation of aortic blood velocity profiles proposed in this paper, is a prerequisite useful for the quantitative analysis of coronary artery disease and aortic stenosis, such as the one described in [8,3]. However, the motivation of this work is not only to solve the problem of the aortic outflow velocity profile registration, but also to present a more general approach for registration of other cardiac images such as mitral valve velocity profiles. Furthermore, the proposed method for registration of the cardiac velocity profiles sets a framework for atlas construction, which can be used for statistical measurements of the population and for atlas-based image analysis. The segmentation of velocity profiles may also be used for signal feature extraction for statistical measurements of variability within population and for classification of velocity profiles into various classes.

2. Background

To the best of our knowledge there are no studies on the analysis of blood flow velocity profiles obtained by Doppler ultrasound published in the literature, apart from the works of Tschirren et al. [11] and Bermejo et al. [12]. Tschirren et al. presented an automated cardiac cycle and envelope extraction of brachial artery flow profile based on image processing operations such as thresholding and correlation. However, this approach is not suitable for the cardiac outflow profiles mainly because it also segments the valve clicks (see Fig. 2), not just the blood outflow. The work of Bermejo et al. analysed outflow profiles that are averaged and manually segmented, with a goal to analyse the valvular dynamics, so this work uses both a different methodological approach and a different hypothesis.

On the other hand, the published research on image registration [13] and segmentation [9] techniques is rather extensive. Since various information from image data is exploited to drive the image registration algorithms, we can classify registration algorithms according to the information content used in registration into algorithms using designated landmarks [14,15], contours [16] and surfaces [17] or various pixel properties functions [18]. The method proposed in this paper is based on the normalized mutual information (NMI) image similarity criteria [19–21] and a specially formulated geometrical transformation.

In [9] segmentation techniques are divided in low-level segmentation techniques (described in [22]) and high-level techniques, where as a major difference between them is the level of the *a priori* information used in the process of segmentation. Although the low-level methods have shown some results on this topic [23], experts usually rely on their experience to produce even better results. To develop a knowledge-based technique and incorporate a domain knowledge various models are used, such as statistical or artificial models based on an expert knowledge. Using a model, experimental data obtained from different subjects are easier to interpret. Preliminary results of using an image from a normal patient as a model are described by Kalinić et al. [24]. The models with a common anatomical substrate are in medical applications often known as atlases. Atlas incorporates useful prior information for segmentation and registration tasks, so variation within population can be described with fewer (transformation) parameters. Atlases have broad application in medical image segmentation and registration and are often used in computer aided diagnosis to measure the shape of an object or detect the morphological differences between patient groups. Various techniques for atlas construction are developed for different human organs, like the heart [25–27] and especially the brain [28–37]. In this paper we use a statistical model as an atlas and an in-silico phantom model for evaluation. The atlas is the mean image, which is an estimate of the statistical expectation of the random field respresenting healthy volunteers.