A Statistical Geometric Model of the Heart

Jens von Berg and Cristian Lorenz

Philips Forschungslaboratorien, Abteilung Technische Systeme, 22335 Hamburg
Email: {Jens.von.Berg,Cristian.Lorenz}@philips.com

Abstract. A comprehensive model of the end–diastolic human heart is presented that covers multiple surfaces like those of the four chambers and the attached vessels. It also contains the three main coronary arteries and a set of 25 anatomical landmarks. The model was adapted to fit 27 clinical multi–slice computed tomography images thus reflecting the anatomical variability to be observed in that sample. The statistical model is intended to provide a priori information for automated diagnostic and interventional procedures. A number of experiments was performed to determine the accuracy of model–based predictions done on unseen cardiac images. Using an additional deformable surface technique, the model allows for determination of all chambers and the attached vessels on the basis of given anatomical landmarks with an average accuracy of 1.1 mm. After such an individualization of the model by surface adaptation the centreline of the three main coronary arteries may be estimated with an average accuracy of 5.2 mm.

1 Introduction

Diagnosis and therapy of cardiac diseases is one of the major issues of today's medicine. Imaging of the cardiac anatomy is addressed by virtually all medical imaging modalities and a considerable portion of clinical interventions concern the heart. From this context arises firstly a demand for preferably non–invasive, accurate diagnosis procedures and secondly a demand for preferably minimally invasive therapeutic procedures. Limited health–care budgets in both fields call for efficient and as much as possible automated procedures. One attempt to facilitate these requirements is the intense use of cardiac anatomical domain knowledge within the related computerized procedures.

2 Related Work

Model based cardiac evaluation procedures have been described for all 2D, 3D or 4D imaging modalities that are capable of imaging the heart, such as 3D echocardiography [1, 2], magnetic resonance tomography (MRT) [3, 4], single–photon emission computed tomography (SPECT) [5], positron emission tomography (PET), X–ray [6], and X–ray Multi–slice computed tomography (MSCT) [7]. As reviewed in [8], most work on 3D images described the left ventricle only that is clearly visible in all imaging modalities. In recent years also the right ventricle

and the atria have been included in some cardiac models, extracted from cardiac MRT scans [9, 10] or MSCT [11]. Image guidance from pre–operative scans is desired during interventions at the left atrium [12]. Multi–slice computed tomography (MSCT) provides images of comparable or even higher spatial resolution than MRT and allows for a fine delineation of the four chambers as well as the trunks of the attached arteries and veins. Considerable less literature is available concerning modelling of the coronary arteries, despite their clinical importance and various attempts for automated or semi–automated segmentation. Dodge et al. reported measurements of the coronary artery locations and diameters based on bi–planar X–ray fluoroscopy data [13]. X–ray fluoroscopy is the gold–standard for coronary artery imaging and reconstruction [14].

3 Contribution

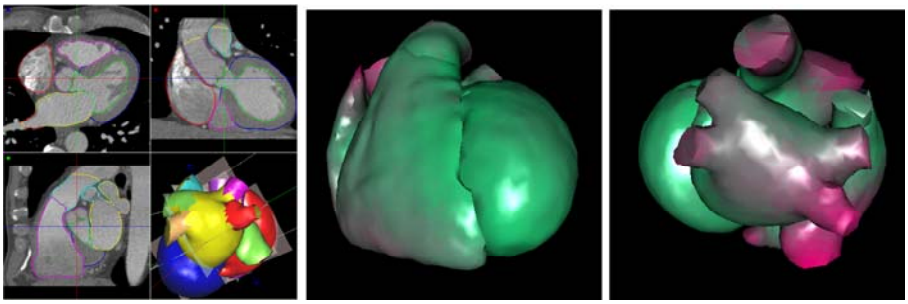
We present a statistical geometric model of the heart that covers the surfaces of the main cavities (atria and ventricles), the trunks of the attached vessels (aorta, pulmonary artery, vena cava, and pulmonary veins), as well as the left myocardium. Although the location of coronary arteries on the ventricles may vary between subjects, the course of the main three coronary arteries can be covered well with a parametric statistical model [15]. We included their centrelines the comprehensive model. A mean model was built by co–registration of manually or semi–automatically performed expert–delineations for 27 end–systolic cardiac data sets. In addition to surfaces and coronary centrelines, a set of 25 anatomical landmarks was manually depicted in the training images serving as a reference frame and for model initialisation and cross–validation. Model individualization is enabled by the automated adaptation of the surface model to an unseen MSCT image by a shape constrained deformable surface model method.

4 Methods

While the triangular multi–surface model (Fig. 1 left) was constructed in a bootstrap fashion using clinical MSCT images [11], the scheme of the coronary model was taken from [13] and it was individualized to the same MSCT training images. As manual expert surface delineation was achieved by deformation of a given model template, a Procrustes analysis could be done by point–based registration using either a rigid (6 degrees of freedom, DOF), a similarity (7 DOF), or an affine (12 DOF) transformation. The residual distances from that mean model reveal the anatomical variability of different cardiac structures beyond the global transformation of the Procrustes registration.

The automated surface model individualization was realized by shape constrained deformable surface models [4]. This method used both shape similarity to the a priori model and attraction by image features in an energy minimization approach [16]. A global point–based pre–registration was achieved using the anatomical landmark set to initialise the deformable model.

Fig. 1. Left: Multi–surface heart model constructed from an MSCT image. Right: Distribution of shape variability in the patient sample after affine co–registration.



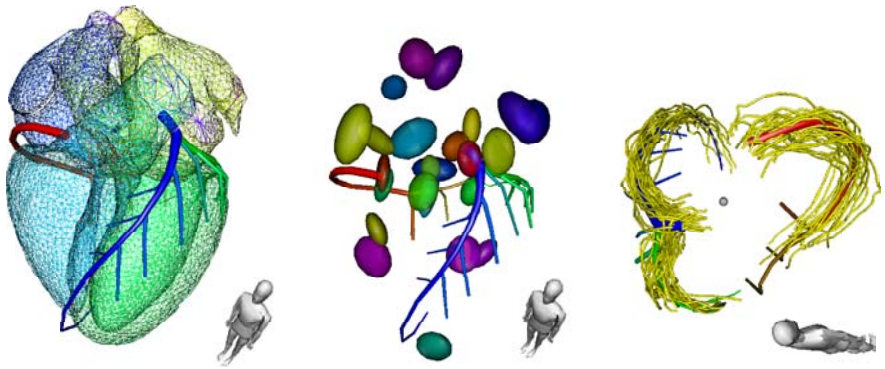
5 Results

The mean residual variability of surface vertex positions after Procrustes analysis ranged from 5.6 mm (rigid) via 4.7 mm (similarity) to 3.6 mm (affine). Most of the variability is to be observed in pulmonary vein trunks, vena cava, and right atrium (Fig. 1). The ventricles are less variable, their values range below the above mean values. These findings compare well with those of the variability of the main coronary arteries that are attached to the ventricles and showed 3.8 mm for rigid, 3.3 mm for similarity, and 2.0 mm for affine registration as acquired in [15]. The mean residual variability over all landmark positions after Procrustes analysis was 9.1 mm (rigid), 7.7 mm (similarity), and 6.7 mm (affine). An unknown landmark position may be estimated from a set of other given well–chosen landmarks with a mean error of about 6 mm. The same holds for the localisation of the main coronary artery centrelines from some given landmarks.

Fig. 2 left shows the mean triangular surface model overlaid with the mean coronary model, which were built independently from it. The anatomical landmarks and their remaining variability after a global co–registration by the coronary centrelines are shown in Fig. 2 centre as error ellipsoids in the model co–ordinate system. Fig. 2 right shows the variability of coronary artery centrelines manually delineated in the patient sample after co–registration of their corresponding cardiac surfaces. The coronary artery model was adapted to minimise the summed distance to all these individual centrelines.

A mean surface model built from a subset of patients and adapted to the remaining images yielded a mean distance of 3.1 mm to reference expert data after the global landmark–based pre–registration (similarity). The distance of vertex v_1 in surface s_1 to surface s_2 was calculated determining the closest point in a local patch surrounding the corresponding vertex v_2 in s_2. Such a patch included all neighbour triangles with a maximal triangle distance of 3 from v_2. The subsequent automatic deformable surface adaptation improved this result to a distance of 1.1 mm averaged over all subjects and all anatomical regions. When the globally pre–registered model is used to estimate the main coronary position, a mean centreline distance of 5.4 mm (similarity) or 5.2 mm (affine) can be observed to the manual delineated centrelines.

Fig. 2. Left: The mean surface model registered with the mean coronary artery model. Centre: Anatomical landmarks with their error ellipsoids registered with the mean coronary artery model. Right: Remaining variability of coronary artery centrelines.



6 Discussion

A statistical model of the human heart was presented that covers surfaces of all four chambers and the attached vessel trunks, the centrelines of the three main coronary arteries, and a set of 25 cardiac anatomical landmarks. The variability of cardiac substructures in a sample set of 27 end–diastolic multi–slice CT images was analysed. The model was mainly used to estimate shape and position of cardiac substructures by the use of other cardiac substructures (e.g. surfaces by landmarks, coronaries by surfaces). The surfaces may be also automatically deformed to fit the respective image boundaries. The application of the surface model for fully automatic cardiac analysis is currently employed [17].

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