Derivation of Clinical Parameters from Three-Dimensional Transesophageal Echocardiographic Image Sequences

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The 3D transesophageal echocardiography (3D-TEE) allows a volumetric acquisition of the beating heart with high spatial and temporal resolution. To exploit a maximum of information and to gain quantitative clinical parameters, a 3D reconstruction process is required which compensates for motion artifacts. The here presented approach is based on dynamic active contour and surface models which represent a priori information about shape and dynamic behavior of the left ventricle. The derivation of functional parameters requires the detection of endo- and epicardial boundaries. Our detection algorithm takes them as dynamic surfaces in the reconstructed sequential volume data set.

3D image reconstruction, active contours, motion estimation, functional imaging, wall movement analysis

1. The Imaging Modality

Early diagnosis of coronary heart disease and monitoring of post-infarction therapy require imaging of shape and dynamic of the left ventricle with high spatial and temporal resolution. The multiplane transesophageal echocardiography (mTEE) is able to meet these requirements. Its performance, portability, low-invasiveness, and relative low cost established this modality in clinical routine.

In mTEE a transducer probe is introduced into the esophagus to acquire ultrasonic images of different planes through the heart from inside the body. The essential feature of mTEE is the ability to rotate the phased array [1]. This allows an arbitrary choice of the imaging plane. Furthermore the absence of disturbing organs like lungs and ribs between transducer and heart opens a large acoustic window. The imaging plane can be selected manually by the examinator during image acquisition or by a computer controlled motor drive. The latter facilitates the acquisition of volumetric sequences of the heart [Fig. 1][2,3]. With this so called three-dimensional transesophageal echocardiography (3D-TEE) one sequence of images per

heartbeat is acquired for each imaging plane. To provide for correlation between the different planes, the image acquisition is ECG-triggered and gating of respiration and heart rate is applied.

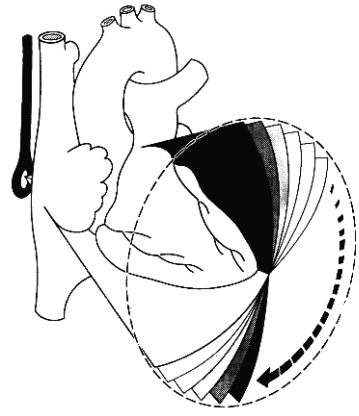

Fig. 1: Acquisition of a volume data set of the heart in 3D-TEE

2 Image Processing

2.1 3D-Reconstruction

Triggering and gating respectively do not guarantee a fixed relation between transducer and heart during the entire acquisition process (typ. 5 min). Any motions of the patient or swallowing movements result in displacements of the transducer. Thus different planes are acquired from slightly different transducer positions. These displacements lead to motion artifacts in uncorrected volume data sets that cannot be neglected.

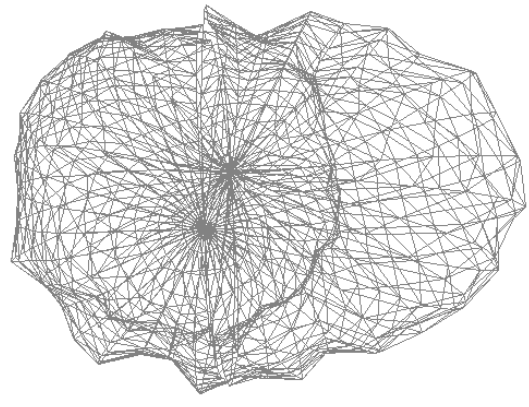

Fig. 2: Uncorrected 3D-reconstruction of manually drawn contours (apical view)

Commercially available systems answer this problem with interpolation thus reducing the spatial resolution beyond a measure that is clinically required. Therefore a correction of the displacements is necessary before the reconstruction of a three-dimensional data set. As there is no information available about the position of the transducer probe during image acquisition, information contained in the image itself must be used in order to estimate the displacements.

The first step in estimating is the automatic detection of a myocardial border that can be found in all image planes but that does not need to be clinically meaningful at this moment.

The automatically detected contours are fit to a common surface in three-dimensional space. Thereat the model of the 3-D-surface encodes a-priori knowledge about the shape of the myocardium. Parameters of the surface model as well as parameters describing translation and rotation of the contours are changed iteratively in order to minimize a cost function that penalizes both, the amount of translation and rotation of the individual planes and the deviation between the contours and the surface model. After computation of the displacements of all planes the set of 2D-image sequences is resampled into a 3D-volume sequence. The task of finding the anatomically correct inner and outer borders of the myocardium can be carried out using these volume data sets.

2.2 Feature Extraction

The automatic boundary detection relies on feature images extracted from the echocardiographical input images. As ultrasonic imaging is based on the scattering of sound at inhomogeneties, homogeneous regions do not contribute to the signal. Typical of biological tissue is the stochastic distribution of small inhomogeneties called scatterers. In biological tissue the average distance between neighboring scatterers is smaller than the spatial resolution of the ultrasonic imaging system. Thus interference of scattered waves emanating from neighboring scatterers results in speckle patterns typical of ultrasonic images. Having a noisy occurrence these speckle patterns contain information about the scatterer distribution [4]. In order to examine the relation between the object features (scatterer distribution) and the image features (speckles) we have developed a simulation system of the imaging process.

Statistical parameters of the amplitude distribution of simulated raw data and reconstructed images are analyzed in order to obtain features related to the scatterer distribution. Significant features are grouped to form a multi-dimensional feature space that separates different kinds of tissue. Local statistical estimators are examined as feature extractors [5].

Apart from features that can be extracted out of static ultrasonic images, local motion can be considered as a feature available from image sequences [6]. Local motion represented by motion vector fields utilizes the correlation between neighboring frames. In our approach this information is used to stabilize the process of contour extraction. By representing additional features for the contour detection coupling of the motion vector fields to the contour model is achieved. On the other hand smoothing the motion vector field along the extracted contours supports the computation of the motion vector field.

2.3 Boundary Detection

A stable detection of contours in noisy images with low SNR requires the exploitation of all available information. In case of 3D TEE data sets there are three sources of information: knowledge about shape, structure and dynamic behavior of the observed object, knowledge about the imaging process and finally the actual acquired data set.

In our approach, the a priori knowledge about the object is used to define an appropriate model of the endo- and epicardial contours. We apply an active surface model which takes these boundaries as elastically coupled membranes with variable distance. This allows to track both contours simultaneously which stabilizes the detection process in case of local uncertainties. Spatial deformation, the inter-membrane distance as well as the temporal evolution are assumed to be smooth. In an active surface model these assumptions are represented by inner energies like bending and stretching energies in conjunction with an inert mass and damping.

Now the model has to be adopted to the actual image data. The first step is to extract a multidimensional feature set as described above. The second step is the transformation of this feature set to an external energy. Thus the actual boundary detection problem is converted into the problem of minimizing the total energy. The latter problem is solved by a finite elements approach. Models with a single active surface were already successfully applied to CT images [7], whereas the idea of simultaneous tracking of endo- and epicardial contours was proved to work for 2D-echocardiographic sequences [8].

2.4 Parameter Extraction

A frequently used diagnostic parameter for assessment of the cardiac function is the regional wall motion. However this parameter is strongly dependent on the chosen reference coordinate system thus masking certain abnormalities. As regional wall thickening is unaffected by the choice of the coordinate system, it is better suited for quantitative statements about myocardial function. This however needs the contour of both, the endo- and epicardium to be known.

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