Monitoring Treatment Outcome: A Visualization Prototype for Left Ventricular Transformation

Stefan Wesarg

Interactive Graphics Systems Group (GRIS), TU Darmstadt, Germany

Abstract. The analysis of cardiac dynamics – especially of the left ventricle – is a means for evaluating the healthiness of the heart. In case that a malfunction has been detected and afterwards has been treated, the question arises whether the treatment was successful or not. On a longer time scale, it is of clinical interest to compare the results of follow-up studies with those of former examinations.

In this paper, we address both issues by presenting a visualization prototype for the comparison of left ventricular dynamics obtained from cine-MRI data. Our approach is based on the computation of differences for standard cardiac parameters between two time series which have been acquired prior to and after treatment. For their visualization, we use a series of bull's-eye displays allowing for an in-depth examination of the treatment outcome. Here, we focus on the special clinical application *ventricular reduction surgery* where we perform a retrospective evaluation for cine-MRI data acquired prior to and right after surgery as well as several months later. We compare our results with diagnosis information obtained from clinical experts.

1 Introduction

In cardiac imaging, the heart is captured at multiple points in time allowing for an examination of its dynamics. There, cardiologists are mainly interested in detecting any abnormalities related to the contraction and relaxation of the left ventricle (LV). For this purpose, cine-MRI (magnetic resonance imaging) is the imaging modality of choice that provides a series of 3D volumes which cover the whole cardiac cycle. In these data sets, the blood pool of the LV has different gray values compared to the myocardium, which permits to easily segment these two regions. Based thereon, the volume of the LV can be computed, and the two boundaries of the myocardium – endocardium and epicardium – can be defined.

Standard LV analysis uses the volume of the blood pool in order to extract end-systole (ES) as well as end-diastole (ED). Afterwards, cardiac parameters are computed [1]. In 2002, the American Heart Association (AHA) has published a set of recommendations concerning LV analysis [2]. The most important issues are the segmentation of the LV into 16/17 regions and the usage of a *bull's-eye* (BE) display for a standardized visualization.

Hennemuth et al. [3] employed a BE display for the visualization of perfusion information and delayed-enhancement image data. The approach presented by

D.N. Metaxas and L. Axel (Eds.): FIMH 2011, LNCS 6666, pp. 121–128, 2011.

de Sa Rebelo et al. [4] uses BE displays in order to show the three components of velocity vectors for the endocardial wall motion. Mantilla et al. [5] visualized computed radial and longitudinal contraction as well as torsion values for the LV in a BE display. A method for computing the degree of asynchronous wall motion and wall thickening has been introduced by Wesarg & Lacalli [6]. There, a BE display is used for the visualization of the corresponding values. A visualization combining 3D rendering and a BE display has been proposed by Termeer et al. [7]. Coronary territories derived from simulated perfusion data are color coded in both visualizations, and in addition, the coronary arteries are projected onto the BE plot. In order to distinguish between a normal and a hypokinetic heart, Kermani et al. [8] compute the *path length* and visualize these values in a BE display.

Most of the aforementioned works employ one single, static BE display for the parameter visualization. Solely, the approach by de Sa Rebelo et al. [4] uses simultaneously two BE displays – one showing the parameters at ED and a second one for ES. A visualization method for cardiac dynamics which employs a set of polar plots and that is closely related to our work has been introduced by Breeuwer [9]. The so-called *uptake movie* consists of successive images which represent the uptake of a contrast agent in the myocardium for the purpose of perfusion examination. In conjunction with the *perfusogram* – a rectangular layout of temporal and spatial perfusion parameters – a convenient navigation through the uptake movie is provided.

The computation of cardiac parameters can be performed for a single study only, i.e. analyzing cine-MRI data acquired at one specific day. However, the examination of changes of LV dynamics over a longer period is also of clinical interest. This may be a monitoring of medication related effects or a follow-up

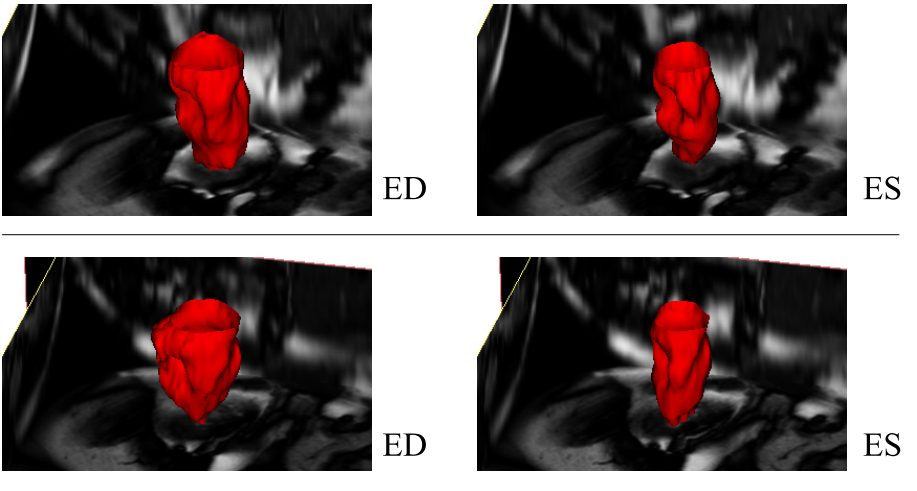

Fig. 1. Ventricular reduction surgery where the apical region is modified. The upper row shows the pre-operative situation, the lower row the status a few days after surgery.

study for investigating surgery outcome. In this work, we focus on the latter where the change of cardiac parameters caused by *ventricular reduction surgery* (VRS) [10,11] is examined. Our data sets originate from patients where the apical region has been reduced in order to give the LV a *better* overall shape (Fig. 1). For the visualization of surgery outcome, the standard static $2D$ representation of the BE display is extended to a $2D+t$ representation. Dynamic BE data is computed for two cine-MRI data sets: a first one acquired prior to surgery and a second one a few days and a few months, respectively, after the intervention. Computing the differences of cardiac parameters between these two data sets allows for a quantification and a detailed examination of left ventricular transformation.

2 Computation of Left Ventricular Transformation

Cardiac image data. Clinical cine-MRI data used for the analysis of left ventricular dynamics is typically represented as short axis (SA) slices. Employing an algorithm specifically designed for the segmentation of the left ventricle, the endocardium as well as the myocardium of the LV can be extracted for all N time steps. We use our own semi-automatic segmentation approach [12] for the extraction of the left ventricular blood pool as well as endocardial borders. However, the method described here is independent from the used segmentation algorithm. In addition to the LV extraction, we obtain a division of the LV into 16 segments (apex is neglected) for each single volume of the time series. For each of the segments, the regional volume is computed and the endocardial (and epicardial) boundaries are sampled on a regular grid of size $I \times J$ (Fig. 2, *left*). Thus, the BE data consists of a number of equally distributed values which represent a specific parameter.

Based on the delineated cine data, the geometrical measure *endocardial distance* Λ^n $n \in \{1, \ldots, N\}$ – being the distance of the sampled wall positions from

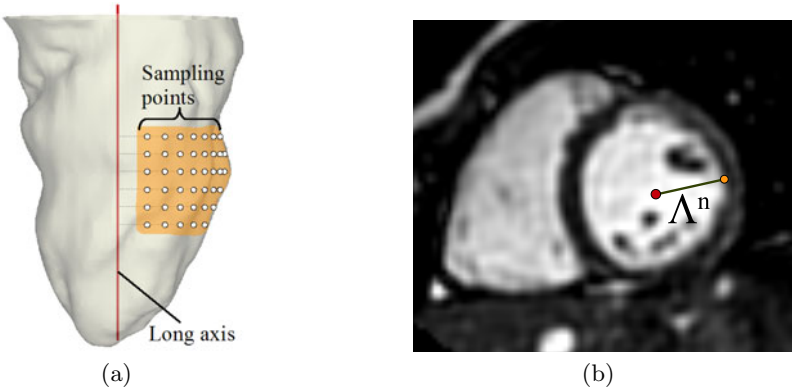

Fig. 2. Sampling of the endocardial border for one mid-cavity segment. The $I \times J$ sampling points are equally distributed over the segment of the endocardium (a) and the corresponding distances Λ^n from the long axis can be computed (b).

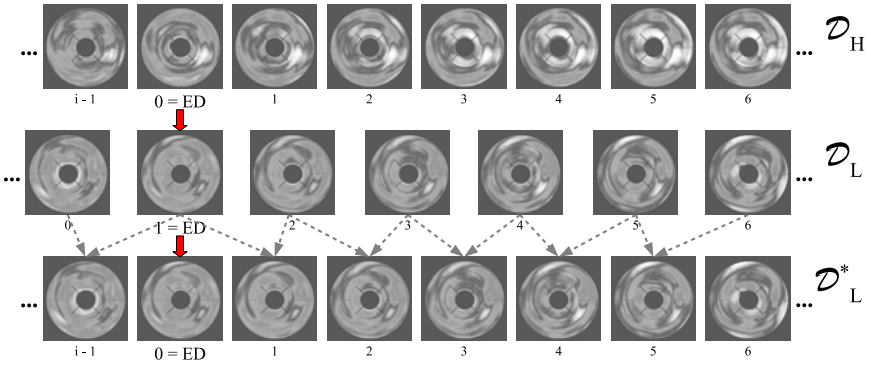

Fig. 3. Two sets $\mathcal{D}_H$ and $\mathcal{D}_L$ of dynamic BE data with different temporal resolution i and j are aligned in order to match ED. The lower resolution data set $\mathcal{D}_L$ (*middle*) is upsampled to $\mathcal{D}^*_L$ using a linear interpolation of the values (*bottom*).

the LV long axis – (Fig. 2, *right*) can easily be computed. Similarly, the *regional volume* Ω^n of the blood pool covered by each of the 16 segments can be derived. If these values are available for each of the N time steps, a series of BE data can be obtained. Thus, in contrast to the conventional approach, where one single BE display – typically related to ED and ES – is computed, we generate a series of BE data comprising all time steps. (Here, we consider only the blood pool and its boundary – the endocardium. But, similar computations can also be performed for the myocardial wall thickness.)

Temporal alignment. We aim on the comparison of two cine-MRI data sets. Assuming that for each of them the segmentation, the sampling of the boundaries as well as the computation of the BE data has been done for all time steps, the BE data has to be aligned spatially as well as temporally in order to compute differences for the cardiac parameters. This alignment could be done on the cine-MRI data directly. For this, several methods have been proposed: spatio-temporal free-form registration [13], level-set motion [14], multichannel diffeomorphic demons [15].

In contrast to these works, we follow a straightforward matching approach based on the BE data and not on the cine-MRI data itself. Spatial correspondence between the BE data is given, since the initial image data has been aligned corresponding to the AHA recommendations and the boundaries are sampled with the same number of points. Due to the fact that in the majority of cases, the temporal resolution is different, a temporal interpolation for the BE data has to be performed. Here, we ignore the rotational motion and deformation since the temporal resolution of our data sets differs only slightly: up to 2 time steps per cardiac cycle.

For performing the temporal alignment, the BE data $\mathcal{D}_H$ with the higher temporal resolution is selected and the BE data $\mathcal{D}_L$ for the other data set is interpolated (Fig. 3). This is done by first aligning the ED phases of both data

sets and afterwards computing the missing information. For each time step where data exists in $\mathcal{D}_H$, new values for $\mathcal{D}_L$ are interpolated linearly. Thus, a temporally upsampled data set $\mathcal{D}_L^*$ is obtained.

Computation of difference values. After the temporal alignment, the difference values for the parameters *endocardial distance* Λ^n as well as *regional volume* Ω^n between two image acquisition dates can be computed. For instance, the differences between pre-operative and post-operative situation are given as: $\mathcal{L} = \mathcal{D}^{\Lambda}_{post} - \mathcal{D}^{\Lambda}_{pre}$ and $\mathcal{O} = \mathcal{D}^{\Omega}_{post} - \mathcal{D}^{\Omega}_{pre}$, respectively. This results in new dynamic BE data sets $\mathcal{L}$ and $\mathcal{O}$ describing each parameter change caused by the treatment.

Visualization. The computational output of the above steps is a set of difference values which are related to specific positions in a BE display. Considering the fact that these values are available for all time steps, *dynamic BE displays* for the changes of endocardial distances as well as regional volumes can be created. For their visualization, several approaches can be used: interactively scrolling through the stack of BE displays, using a multiple window layout, dynamic visualization as animation loop. The computed parameter values are displayed by mapping them to color. For this, we use a perceptually based color map[1] (Fig. 4). The value ranges for this mapping are $(-10 \ldots 10\,mm)$ for the endocardial distance differences and $(-5 \ldots 5\,ml)$ for the regional volume differences. These settings are based on normal value ranges given in the literature [16,17].

3 Clinical Example

Our clinical partner provided us cine-MRI data obtained from over 30 patients who underwent VRS. That data comprised the pre-operative situation, the post-operative status a few days later as well as image data from a follow-up study performed several months after surgery. Due to space constraints, we show results for only one representative patient who underwent VRS.

The diagnosis reported a slightly improved overall LV function right after surgery (global EF increased from 36 % to 38 %) but a re-deterioration – occuring quite often for those patients [11] – seen in the follow-up study with a newly increased size of the LV and dramatically reduced EF (now only 28 %). Using our method, these findings are confirmed and can be investigated in more detail. For this, the differences between the values of the endocardial distances and of regional volumes related to the pre-operative situation (18 time steps) and those values for the post-operative (18 time steps) and follow-up data (16 time steps), respectively, are displayed.

Right after surgery (Fig. 4, *top*), the apical wall does virtually not move at all. The endocardial distances for these regions are larger around ES but smaller around ED compared to the pre-operative ones. In addition, the distances in the basal regions are increased around ED, thus compensating for the reduced apical

[1] Taken from `http://colorbrewer2.org`

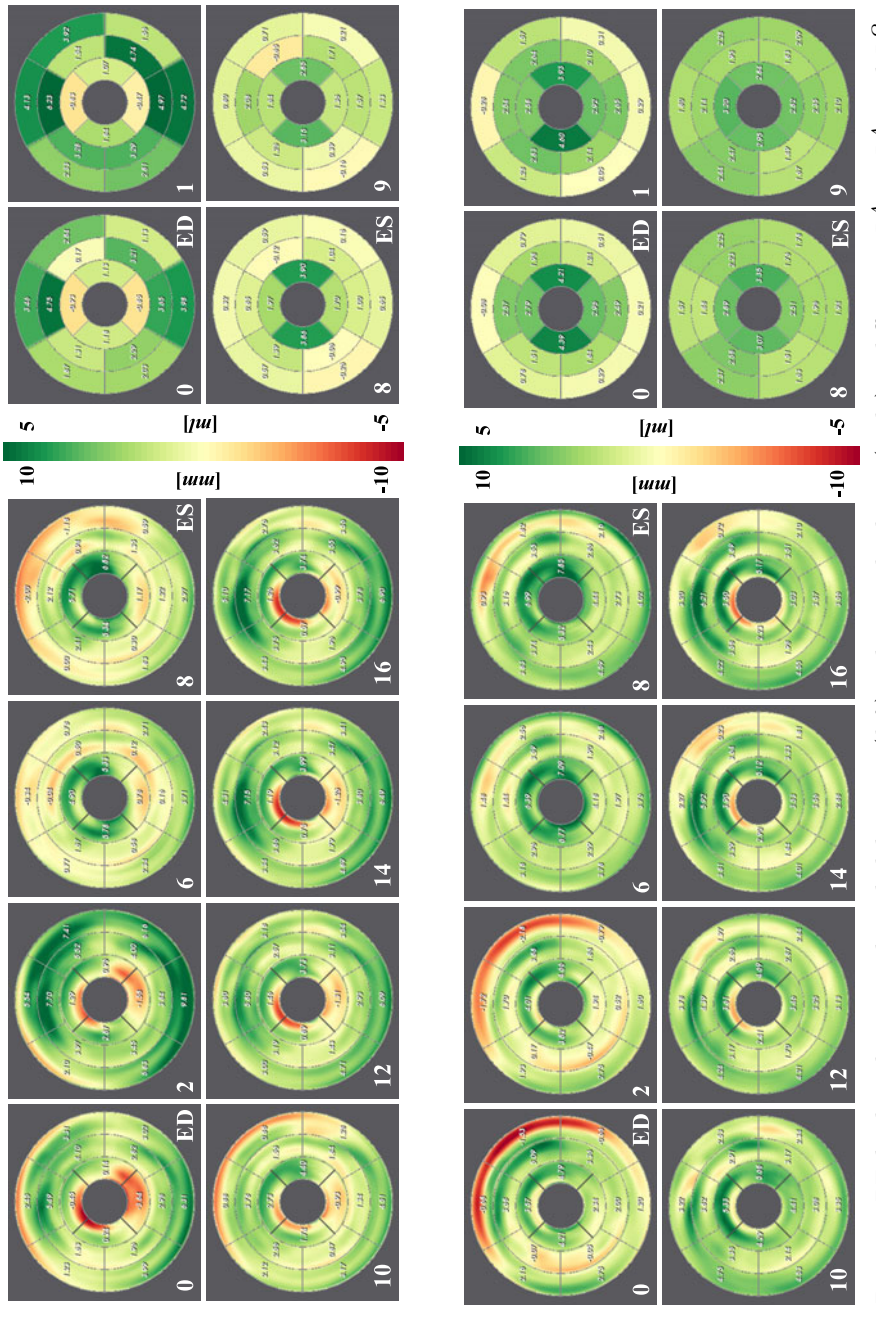

Fig. 4. Dynamic BE displays showing endocardial distances (*left*) and regional volumes (*right*) as differences $\mathcal{D}^{\Lambda}_{post} - \mathcal{D}^{\Lambda}_{pre}$ and $\mathcal{D}^{\Omega}_{post} - \mathcal{D}^{\Omega}_{pre}$, respectively (*top*) as well as differences $\mathcal{D}^{\Lambda}_{f.-up} - \mathcal{D}^{\Lambda}_{pre}$ and $\mathcal{D}^{\Omega}_{f.-up} - \mathcal{D}^{\Omega}_{pre}$, respectively (*bottom*). See text for further explanations.

regions. Consequently, the regional volume displays show significantly increased values for the apical region around ES and an increase for the mid-cavity and basal segments around ED.

Nine months later (Fig. 4, *bottom*), the wall distances for the apical regions are even larger than before surgery. Between basal anterior and lateral regions the endocardial distances are decreased. The end-systolic volume values for basal and mid-cavity regions are increased showing a lowered contractibility of the LV. In addition, the apical LV volume values are globally increased.

4 Discussion

In this work, we have presented an approach for an improved visualization of cardiac parameters related to left ventricular transformation. For this, we have adopted the idea of Breeuwer [9] to display a set of successive polar plots and extended it to a comparison of two dynamic cardiac image data sets. In case that two or more 4D data sets for the same patient are available, our method allows for an in-depth examination of the temporal evolution of cardiac parameters. Differences between the cardiac parameters can be computed and dynamic BE data can be generated. Choosing the clinical application VRS, we have shown how to benefit from our approach for gaining more insight into the changes of cardiac anatomy and function. Furthermore, it can directly be applied to other clinical purposes where the monitoring of treatment outcome after cardiac surgery or drug administration is of interest.

As an extension of the recommended usage of a BE display as preferred means for visualizing the analysis results for the LV [2], the dynamic BE display can easily be understood by cardiologists. There is no need for adapting to a new visualization method, nor is the visualization overloaded with too much information. Solely the temporal dimension is added to the display, making the information accessible which is available in any case. The visualization method presented in this work is currently in a prototypic stage. Initial tests with clinical images from our database related to VRS patients – containing data for over 30 patients – show evidence for providing more detailed information. However, an extensive clinical evaluation is needed for an ultimate verification of the assumed benefit.

Acknowledgment. We want to thank the Department of Thoracic and Cardiovascular Surgery of the J.W. Goethe University Frankfurt, Germany for providing us the image data and sharing the diagnosis information.

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