CMR–based Modelling of the Left Ventricle: a Tool for Functional Assessment and Surgical Decision Support

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Abstract — The most challenging objective of the clinical decision making in the management of patients with myocardial dysfunction is to choose the best option for improving myocardial function and clinical outcome.

The present work aims at developing patient-specific computational models to assist cardiologists and cardiac surgeons in defining the severity and extent of disease in patients with left ventricular (LV) dysfunction, with or without mitral regurgitation, and in supporting clinical decision making and planning of the optimal treatment for left ventricle-valve repair. Two software were developed: the Functional Assessment Tool (FAT) provides cardiologists with the automatic extraction of quantitative MRI-derived parameters about LV performance; the Functional Predictive Tool (FTP) allows cardiac surgeons for easy and fast simulations of post-operative scenarios for different surgical choices.

FAT validation, focused on LV dimension and function indices, demonstrated a good ability in detecting endo- and epicardium and provided results comparable to the gold standard. Preliminary simulations of surgical procedures using FTP allowed to calculated segmental circumferential and radial strains with sufficient accuracy.

Future developments will include the tuning of simulation parameters used accordingly with the feedback of clinicians and the effects of changes in peripheral resistances and heart rate, typically associated to post-operative scenarios.

I. INTRODUCTION

Dilated cardiomyopathy following ischemic disease increases the degree of heart failure and its surgical management remains controversial. The most challenging objective in the clinical decision making for the management of patients with myocardial dysfunction or overt heart failure (HF) is to choose the best option for improving myocardial function and the clinical outcome. Medical versus surgical and, among surgical options, coronary revascularization, myocardial restoration, mitral valve repair, are the proposed solutions for avoiding progression of cardiac dysfunction toward HF. Magnetic resonance imaging (MRI) can provide patient-specific identification of dysfunctioning left ventricular (LV) segments and recognition of not viable myocardium by gadolinium (GAD) late hyper-enhancement pattern.

Within EU project VPH2 we aimed at developing two software tools for the quantitatively prediction the post-operative mechanical performance of the complex left ventricle: a functional assessment tool (FAT) and a functional predictive tool (FTP). In particular, the former is aimed to the automatic extraction of contours from 4D MRI images and automatic calculation of global and regional parameters (e.g. EF, synchronicity) while the latter is aimed to the prediction of postoperative LV function through mechanical modeling.

II. MATERIAL AND METHODS

A. CMR imaging

A group of 15 patients with previous myocardial infarction, manifesting regional wall motion abnormalities, was considered. CMR studies were performed using a 1.5 Tesla scanner (Signa Hdx, GE Healthcare, Milwaukee, Wisconsin). An eight-element cardiac phased-array receiver surface coil with breath-holding in expiration and ECG-gating was used for signal reception. Three standard cine long-axis slices and a stack (from 8 to 12) of contiguous cine short-axis slices from the atrio-ventricular ring to the apex were acquired using a steady-state free-precession pulse sequence (30 phases, slice thickness 8 mm with no overlap and no gap, FOV = 40 cm, reconstruction matrix 256 x 256, TR= 3.5 ms, TE=1.5 ms, flip angle 45°).

B. FAT

FAT is a software tool for MRI semi-automatic segmentation of endo- and epicardium. Two segmentation strategies were included in the tool. For endocardial detection (Figure 1.a), the region-based approach was chosen. Briefly, after initialization of some algorithm’s parameters and after the selection of one point inside the LV cavity, the applied algorithm expands the initial videointensity probability distribution. The algorithm uses the detected contour as initialization for the next slice. For epicardial detection, the algorithm to be used is the based on the edge-based level-set that requires an initialized contour in the neighbor of the contour to be detected to correctly operate. The contour initialization can be provided manually or the previously detected (if present) endocardial contour can be used.

After
the endo- and epicardial contours have been detected from base to apex, the software automatically computes the LV volume and the LV mass.

Once all the contours were detected, the ED centroid of the LV cavity was calculated and used as the origin of segmentation. An additional point was then manually placed at the junction between the right ventricular free wall and the interventricular septum on the ED frame. Starting from that point, the LV cavity was divided into six 60° wedge-shaped segments. For each segment, regional fractional area (RFA) in % of regional end-diastolic area (REDA) was calculated automatically throughout the cardiac cycle using a fixed-coordinate reference system. From these 6 curves in each slice, regional fractional area change (RFAC) was computed as the difference between max and min RFA, expressed in % of the regional end-diastolic area (REDA). These values for each segment were used to automatically interpret wall motion as normal (RFAC>=50%) or abnormal (RFAC<50%).

C. FAT Validation

The validation was focused on the LV dimension and function indices usually computed from the cardiac MRI images, such as end-diastolic (ED) and end-systolic (ES) LV volumes, stroke volume (SV), ejection fraction (EF), LV mass computed both at ED and ES. For these measurements, the “gold standard” is represented by the result of the manual tracing of endo- and epicardial LV contours that an expert cardiologist performed on a subset of patients.

The MRI data were analyzed using commercial software (MASS 6.1, Medis, Leiden, the Netherlands). The expert cardiologist proceeded into the conventional analysis of these images, by manual tracing endo- and epicardial LV contours. Biventricular volumes, function and LV mass were measured using standard volumetric techniques with that dedicated software. Results for each parameter were compared to the “gold standard” by linear regression and Bland-Altman analysis. The goodness of the linear fitting of the two measurements was evaluated the r2 coefficient of the regression. Bias (in absolute and % values) and 95% limits of agreement were computed for each parameter. Also, to test the performance of the developed procedure in order to automatically detect possible wall motion abnormalities, a “gold standard” for wall motion interpretation was decided as the visual interpretation of the dynamic images from the same expert cardiologist who performed the contour tracings. a software tool for MRI semi-automatic segmentation.

D. FPT

FPT is a software tool for MRI modelling of post-operative mechanical performance of the complex left ventricle. The left ventricle is divided into 6 longitudinal sections and 3 circumferential sections, for a total of 18 segments (Figure 1b). For each segment we applied a nearest neighbour correction algorithm to compute segmental time-variant strains both in longitudinal and circumferential direction from 4-D short-axis cardiac magnetic resonance imaging data. The software tool allows to calculate independently or in combination: 1. the simulation of the restoration procedure so to provide the new ventricular shape, dimension and performance (Bovè et al., 2009); 2. the simulation of the resynchronization of selected regional segments (Sitges et al., 2009); 3. the simulation of the effects of a revascularisation procedure on regions of hibernated myocardium (Braun et al., 2005); 4. the calculation of the myocardial contractility enhancement due to left ventricular end-diastolic volume reduction following the mitral regurgitation correction (Bax et al., 2004).
III. RESULTS AND DISCUSSION

A. FAT Validation

Of the 15 patients, two were excluded for the presence of artefacts in the images that precluded correct performance of the developed algorithm without heavy manual correction. The automated analysis was then feasible in 13/15 (87%) patients.

The time required to process a single frame (ED or ES) from base to apex, for the detection of both endo- and epicardial contours, was approximately 1 min using a standard personal computer. Good correlations were found with gold standard measurements of LV end-diastolic volumes (EDV), end-systolic volumes (ESV), stroke volume (SV) and ejection fraction (EF%). Bland-Altman analysis resulted in minimal bias and narrow limits of agreement in LV ED and ES volumes (Table 1).

Table 1: Linear regression and Bland-Altman analysis results for FAT validation.

<table>
<thead>
<tr>
<th></th>
<th>$r^2$</th>
<th>bias</th>
<th>error% / mean</th>
<th>95% agreement</th>
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<td>EDV</td>
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<td>-2.5 ml</td>
<td>-1.4%</td>
<td>-17.7 ÷ 12.7 ml</td>
</tr>
<tr>
<td>ESV</td>
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<td>-4.2 ml</td>
<td>-4.1%</td>
<td>-15.3 ÷ 6.8 ml</td>
</tr>
<tr>
<td>SV</td>
<td>0.968</td>
<td>1.7 ml</td>
<td>2.1%</td>
<td>-7.6 ÷ 11.0 ml</td>
</tr>
<tr>
<td>EF%</td>
<td>0.9796</td>
<td>1.5 %</td>
<td>3.2%</td>
<td>-3.2 ÷ 6.2 %</td>
</tr>
</tbody>
</table>

B. FPT Preliminary testing

Local strains were calculated for a healthy LV (SUB1) and two late-ischemic LVs (SUB2 and SUB3). Results were consistent with the known LV function.

Preliminary simulations of surgical procedures led to modifications in time-dependent LV volume that agreed with previous clinical results. For SUB1, the measured regional strain curves (Figure 2) provided uniform strain patterns over all myocardial segments; in the systolic phase, all sectors contracted circumferentially and thickened radially. Circumferential shortening increased going from the basal region to the apex: peak absolute values ranged from 15 to 20% for the sectors of the basal and mid region, and from 16 to 24% for the apical sectors. Similarly, the observed thickening was progressively more relevant going from the ventricular base to the apex. The method provided physiologically meaningful circumferential strain curves with small dispersion among LV segments, i.e., they were almost homogeneously distributed from base to apex of the LV consistently with previous findings from the literature (Edvartsen et al., 2002). An increasing thickening from the ventricular base to the apex was noted, accordingly with recent findings (Zhong et al., 2009).

The normal waveform of time-dependent strains, as well as the trend characterizing the changes from the basal to the apical region, was lost in the pathological subjects.

In SUB2 (Figure 3, top panel) maximum circumferential shortenings ranged from 13 to 23%; all of the basal sectors showed a slower contraction and the shortening of one sector in particular was delayed. These anomalies propagated into the mid region, where circumferential shortenings ranged from 7 to 12%. In the apical sector, very irregular pattern of circumferential shortening were
observed, both in terms of maximum values and waveform of the six strain plots. As regards radial thickening of the myocardium, in the basal region maximum values ranged from 40 to 60%, and the most evident anomaly with respect to the normal behavior was detected in the sector characterized also by delayed circumferential shortening.

In SUBJECT 3 (Figure 3, bottom panel), both circumferential shortening and radial thickening showed a time-dependency that was even more abnormal than the one observed in SUBJECT2. Moreover, none of the 18 sectors shortened by more than 6%, thus indicating very poor contraction of the myocardium. Thickening was much lower than in the two previous subjects: maximum values ranged from 6 to 20%, from 6 to 28%, and from 4 to 64% in the basal, mid and apical sectors, respectively.

Preliminary simulations of surgical procedures led to modifications in time-dependent LV volume that agreed with previous clinical results (Figure 4).

Figure 4: (top) Sketch of ischemic region (blue) identification. (bottom) FTP interface: time-varying magnitude of circumferential (blue) and radial (red) strains; pre- and post-operative LV volume after LV restoration.

IV. CONCLUSIONS

FAT proved to be a reliable and time-saving tool for the assessment of LV geometry and function. FTP calculated local strains with sufficient accuracy. Still, its predictive functions need development, by refining already included parameters and adding new ones (e.g. changes in peripheral resistance and heart rate).

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REFERENCES