Extracting Robust Features from Cardiac Magnetic Resonance Image Contours for Detecting Dilated Cardiomyopathy

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Abstract

Aim of this study was to extract robust features from cine magnetic resonance images (MRI) for phase estimation in dilated cardiomyopathy (DCM) patients. The found features may serve as additional diagnostic parameters. Previously found markers could be improved and were applied to an enlarged subject group. Four quantitative features based on the phase deviation between the left and the right ventricle (INTER, INTER-VOL) and the non-uniformity of left ventricluar movements (INTRA, INTRA-VOL) were shown to be significantly different for DCM patients compared to healthy subjects. The noise-resistance of the features allows the utilization of fewer MRT slices and enables to reduce the contour detection accuracy permitting a more feasible analysis of future data.

1. Introduction

In patients with reduced left ventricular function (LVF) the frequently concomitant left bundle branch block (LBBB) leads to a further deterioration of global heart performance due to asynchronous contraction. Implantation of biventricular pacemakers may be an option for these patients [1]. QRS duration alone has failed to serve as predictive parameter for the clinical outcome of patients after biventricular pacing, since ventricular synchronicity does not necessarily require a synchronous electrical excitation [2]. In a previous study [3] we showed the utility of measuring phase differences between the left and right ventricle in MRI pictures. Aim of this study was to improve and robustify the found markers and to apply them to an increased subject group. Furthermore two new promising features based on contour areas were introduced.

2. Methods

2.1. Subject data

The patient group consisted of 17 subjects with dilated cardiomyopathy (DCM) from which 11 had a left bundle branch block (LBBB). The left ventricular ejection fraction (LVEF) in the DCM group had a mean of 27.35% and a standard deviation of 9.17. The control group included 9 healthy subjects with a LVEF of 69.44% and a standard deviation of 4.61.

2.2. Imaging

Imaging was performed on a $1.5T$ whole body scanner (Intera CV, Philips Medical Systems, Software Release 9.1) with Master Gradients (slew rate $150T/m/s$, amplitude $30mT/m$). A 5-element phased-array cardiac coil was used. Three short survey scans were performed to define the position and true axis of the left ventricle. Afterwards, wall motion was imaged during breath holding within long and short-axis slices using a steady-state free precession (balanced fast-field echo) sequence, which provides an excellent endocardial constrast. Cardiac synchronization was achieved by prospective gating. The cine images were recorded with $23 - 32$ frames per heart beat and a slice thickness of $10mm$ ($8mm$ in some cases).

2.3. Image analysis

All endocardial borders of the left and the right ventricle were manually drawn on up to 11 short axis slices for the whole cardiac cycle using the MASS® plus 5.0 Software (Medis, Leiden, Netherlands). Difficulties in the correct tissue assignment were reduced with the observation of adjacent slices and frames in the detection process. The papillary muscles were assigned to the ventricular cavum (see figure 1). The further processing of the contours was performed using Matlab® 6.51 (MathWorks Inc.).
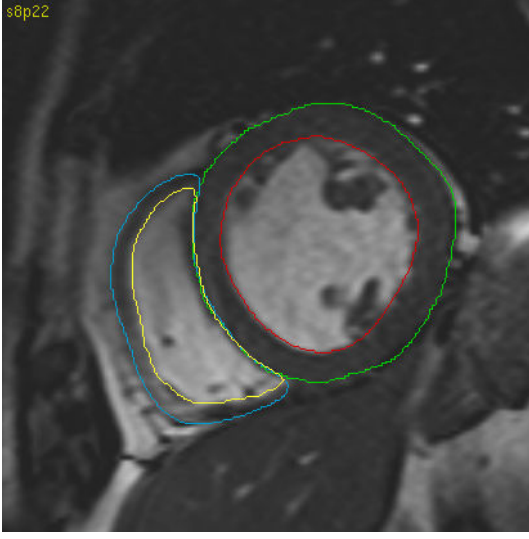
Figure 1. MR short axis slice with hand-drawn contours of all endo- and epicardial borders.
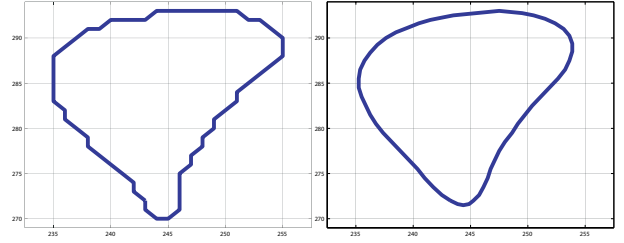

Figure 2. The moving average smoothing procedure is applied to a contour (left diagram). The result after smoothing with window size $w = 4$ is shown in the right diagram.

2.4. Feature extraction

We propose four parameters based on fundamental geometrical properties of the left and the right ventricular endo-cardial borders:

INTER: Asynchronicity between the diameters of the left and the right ventricle.

INTER-VOL: Asynchronicity between the area of the left and the right ventricle.

INTRA: Non-uniformity of the lateral and the septal border movements of the left ventricle.

INTRA-VOL: Non-uniformity of the lateral and septal area changes of the left ventricle.

The computations are perfomed for each slice separately and are combined using a trimmed mean strategy.

The manually extracted contours from the MASS software are Freeman chain encoded closed curves in a two dimensional plane which were first decoded into polygons $\partial B : (x, y)_{k=1}^{n} \in \mathbf{R}^2$ describing boundaries of two-dimensional connected regions $B \subseteq \mathbf{R}^2$. Especially the contours of the outer slices are prone to noise due to the strong fluctuations in the MRI pictures at these locations (e.g. throughplane and valve movements). A circular moving average filter with window size $w = 4$ was used to smooth the curves (see figure 2) and to gain more robust features in the subsequent processing steps. The smoothed contour $(\hat{x}, \hat{y})_k$ is defined as

$$\hat{x}_k = \frac{1}{2w+1} \sum_{j=k-w}^{k+w} x_k \quad \text{and} \quad \hat{y}_k = \frac{1}{2w+1} \sum_{j=k-w}^{k+w} y_k$$

where $x_k := x_{n-k}$ and $y_k := y_{n-k}$ for $-n+1 \le k \le 0$.

The subsequent computation steps require the center of mass $(\overline{x}, \overline{y})$ of a closed region B which can be expressed [4] using the geometric moments $m_{pq} = \int_B x^p y^q d(x, y)$ as $\overline{x} = \frac{m_{10}}{m_{00}}$, $\overline{y} = \frac{m_{01}}{m_{00}}$. For a polygonal border this can be efficiently computed in $O(n)$ steps using the Gaussian integration theorem

$$\int_B \frac{\partial P}{\partial x} - \frac{\partial Q}{\partial y} d(x, y) = \oint_{\partial B} P dy + Q dx \qquad (1)$$

which states that an integral over a scalar field on a closed domain $B \subset \mathbf{R}^2$ (left side) can be expressed by a curve integral along the border ∂B of the domain (right side). The geometric moments m_{pq} can be computed using $P(x, y) = x^{p+1}y^q/(p+1)$, $Q(x, y) = 0$ or alternatively $P(x, y) = 0$, $Q(x, y) = -x^p y^{q+1}/(q+1)$ which can be expressed with the parametrization $\partial B = \{\gamma(t) \in \mathbf{R}^2 \mid t \in [0, 1]\}$ as

$$\int_0^1 P(\gamma(t))\dot{\gamma}_y(t)dt + \int_0^1 Q(\gamma(t))\dot{\gamma}_x(t)dt \quad .$$

Each segment of the polygon is now parametrized with $\gamma^{(k)}(t) = \begin{bmatrix} x_k + t\Delta x_k & y_k + t\Delta y_k \end{bmatrix}^T$ where $\Delta x_k = x_{k+1} - x_k$, $\Delta y_k = y_{k+1} - y_k$, $x_{n+1} := x_1$ and $y_{n+1} := y_1$ so the integral values of the k-th segment evaluate to:

$$m_{00}^{(k)} = x_k \Delta y_k$$

$$m_{10}^{(k)} = -\Delta x_k \left[x_k y_k + \frac{1}{2}(x_k \Delta y_k + y_k \Delta x_k) + \frac{1}{3}\Delta x_k \Delta y_k \right]$$

$$m_{01}^{(k)} = \Delta y_k \left[x_k y_k + \frac{1}{2}(x_k \Delta y_k + y_k \Delta x_k) + \frac{1}{3}\Delta x_k \Delta y_k \right] \quad .$$

For the whole curve the partial moments have to be summed up $m_{pq} = \sum_{k=1}^{n} \hat{m}_{pq}^k$ to obtain the moment. Now the polygons of the left and the right ventricle are intersected with the line $\overline{C_1 C_2}$ connecting both centers to obtain the septal and lateral borders L_i, S_i, $i = 1, 2$ (see figure 3). Furthermore the left ventricle is cut into two parts using the perpendicular of the line $\overline{C_1 C_2}$ running

through the mean center of gravity $M_1 = \frac{1}{T}\sum_{\tau=1}^{T} C_1^{(\tau)}$. Then the areas of the septal and lateral parts A_S and A_L are computed as described. All calculations are processed for each slice $s = 1 \ldots N$ and each frame $\tau = 1 \ldots T$ separately. The INTER measure is defined as the phase difference between the diameters of the left and the right ventricular contour:

$$\text{INTER}^{(s)} := \phi(\|L_1^{(s,\tau)} - S_1^{(s,\tau)}\|, \|L_2^{(s,\tau)} - S_2^{(s,\tau)}\|) \quad .$$

The INTRA measure is defined as the phase difference of the septal and lateral border of the left ventricle to its mean center M_1:

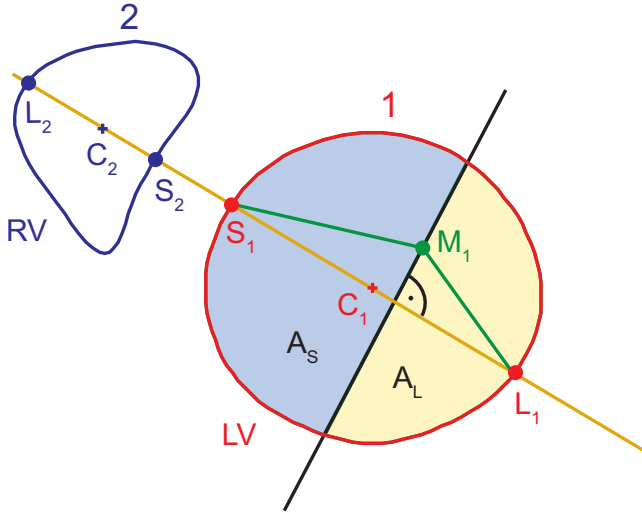$$\text{INTRA}^{(s)} := \phi(\|L_1^{(s,\tau)} - M_1^{(s,\tau)}\|, \|S_1^{(s,\tau)} - M_1^{(s,\tau)}\|) \quad .$$

Figure 3. The septal (S) and lateral (L) borders are obtained by intersecting the connection line between the two centers of gravity of the left and right ventricular contour. The INTRA measure uses the distances of S and L to the mean center M_1 (marked in green) of the left ventricle. The INTRA-VOL measure compares the phase differences between the two areas A_S and A_L.

The two volume based measures are defined as the phase difference between the left and the right ventricular area

$$\text{INTER-VOL}^{(s)} := \phi(A_1^{(s,\tau)}, A_2^{(s,\tau)}) \quad ,$$

and the phase difference between the lateral and septal half-contour of the left ventricle

$$\text{INTRA-VOL}^{(s)} := \phi(A_L^{(s,\tau)}, A_S^{(s,\tau)}) \quad .$$

The phase difference between two time signals $\mathbf{x} = (x^\tau)_{\tau=1}^{N}$ and $\mathbf{y} = (y^\tau)_{\tau=1}^{N}$ was estimated with

$$\phi(\mathbf{x}, \mathbf{y}) := \arccos\left(\frac{\hat{\mathbf{x}} \cdot \hat{\mathbf{y}}}{\|\hat{\mathbf{x}}\| \cdot \|\hat{\mathbf{y}}\|}\right)$$

where $\hat{\mathbf{x}} = \mathbf{x} - \mathbf{1}\bar{x}$, $\hat{\mathbf{y}} = \mathbf{y} - \mathbf{1}\bar{y}$ and $\bar{x}$, $\bar{y}$ were the respective time mean values. All four markers are in the domain $[0, \pi]$. The resulting features were computed using the two aggregation strategies 80% trimmed mean over all available slices (8-11) and 60% trimmed mean of the innermost 5 slices. By construction the proposed features are scale, rotation and translation invariant.

3. Results

All four markers were significantly higher in the DCM group than in the control group (see figure 4). The INTER measure had a p-value of 0.00031, the INTER-VOL 0.00041 and both INTRA measures $6.4 \cdot 10^{-7}$ (U Test). For the distinction between LBBB versus not LBBB within the DCM group only the two intra-ventricular markers were significant (INTRA, $p = 0.02$ and INTRA-VOL, $p = 0.027$). For the reduced experiment with only 5 slices the INTRA-VOL measure even improved to $p = 0.015$ and the INTRA performance remained constant. Only INTRA and INTRA-VOL were in both cases (all slices versus 5 slices) able to separate the DCM group from the control group by a single threshold value (see right diagram in figure 4). Both INTRA markers showed a high performance in the distinction of the DCM group without LBBB to the LBBB group. Since the proposed markers do not use geometrical information over different layers the features are resitant to offsets between slices. Only the two INTER markers were significantly correlated with the QRS duration (all slices: INTRA 0.77 with $p = 0.0003$, INTRA-VOL 0.57 with $p = 0.017$, 5 slices: INTRA 0.75, $p = 0.0006$, INTRA-VOL 0.63, $p = 0.006$). All MRI contours were visually inspected and each subject was graded according to 3 different ratings reflecting the mechanical asynchronity. These ratings were compared to all four features using the interclass correlation coefficient (ICC) [5] leading to INTER: 0.39 (p-value 0.022), INTRA: 0.81, INTER-VOL: 0.41 (p-value 0.024), INTRA-VOL: 0.68. The p-values were estimated with a permutation procedure ($n = 10000$ randomization steps). Both INTRA measures had estimated p-values of 0.0001.

4. Discussion and conclusion

Clinically promising parameters for the quantitative assessment of the phase difference between the left and the right ventricular movements and the non-uniformity of the left ventricular contraction were found and could serve as extra diagnostic parameters in confluence with QRS duration and visual MRI inspection. The previously found results [3] could be verified on an extended subject group. It was shown that the two new parameters INTER-VOL and INTRA-VOL were valuable for the detection of DCM.
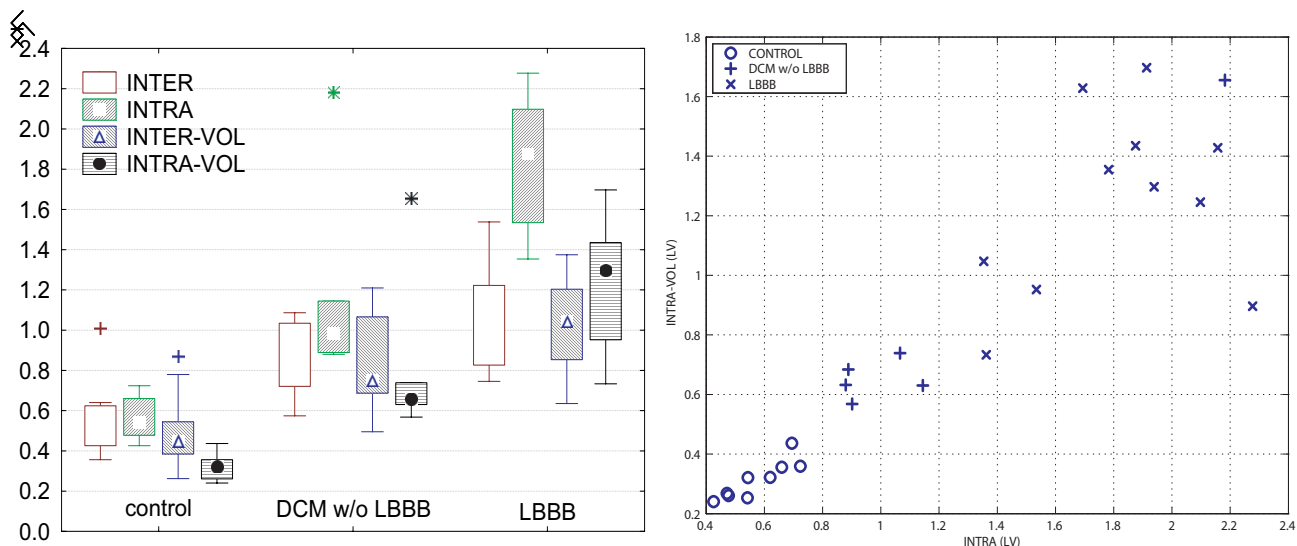
Figure 4. Left diagram: Box-plots of all four features (80% trimmed means) are shown for the three different subject groups (control subjects, DCM patients without LBBB and LBBB patients). Right diagram: Scatter plots for both INTRA measures are shown using an 80% trimmed mean over all available slices. The DCM and the CONTROL group were separable for both features independently by a single threshold.

To give a more rigorous assessment of the robustness it would be necessary to observe fluctuations of the feature values among different observers (interobserver variability). Exemplary this was done with one DCM subject using a very rough drawing process. The right ventricle was drawn very inaccurately. INTER differed by 17% to the original data point whereas all other measures were changed by less than 5.4%. The class assignment of the data point was not affected by these changes.

Future work includes the expansion of the subject groups using only 5 slices and a decreased contour detection accuracy to obtain faster results. Especially DCM cases with low QRS duration and high ventricular asynchronicity would be a confirmation of the method. A further goal is the robust automatic detection of the left ventricular borders.

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