AUTOMATED EVALUATION OF LEFT VENTRICULAR DIASTOLIC FUNCTION USING VELOCITY-ENCODED MAGNETIC RESONANCE IMAGING: CONVENTIONAL AND NEW PARAMETERS

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ABSTRACT

Assessment of diastolic function with phase-contrast (PC) Magnetic Resonance Imaging (MRI) is not used in clinical routine because of the lack of automated analyses. Thus, our aim was to develop a process to automatically analyze PC data. We studied PC data of 25 controls with a custom software, designed for automated segmentation of PC images and analysis of velocity and flow rate curves to derive diastolic parameters. Segmentation was successful on all subjects. Also, our conventional parameters were consistent with those previously presented in the literature and our new parameters highly correlated with those known to have a high prognosis value. Our process may provide a valuable addition to the established cardiac MRI tools.

Index Terms—phase-contrast, heart failure, segmentation, diastolic function

1. INTRODUCTION

Diastolic dysfunction, which is strongly related to the quality of left ventricular (LV) filling, is an early sign of heart failure. Indeed, it has been shown that 40 to 50% of patients suffering from heart failure had a normal systolic function while their diastolic function was impaired [1]. Thus, the early detection of diastolic dysfunction is crucial. In clinical routine, the evaluation of diastolic function is performed using Doppler echocardiography imaging. This technique enables the estimation of diastolic conventional parameters such as the transmitral flow-related early peak (E) and late peak (A) velocities and the deceleration time (DT), as well as the myocardial early peak (Ea) longitudinal velocity at the mitral annulus. The associated ratios E/A and E/Ea, as well as DT, were shown to have a high prognosis value [2].

MRI, with its recent developments in velocity encoding, is increasingly used for the analysis of through-plane flows and myocardial velocities. Few studies demonstrated the usefulness of PC MR images in the evaluation of the above diastolic conventional parameters. However, the analysis of such images was mostly based on manual positioning of regions of interest (ROIs) within the transmitral flow area or the myocardium on multiple phases [3, 4]. This manual segmentation is time-consuming and operator-dependent.

Accordingly, our primary goal was to develop a robust segmentation to automatically delineate the transmitral flow and the myocardium throughout the cardiac cycle. We hypothesized that the excellent quality of PC data, in terms of spatial and temporal resolutions, combined with an accurate segmentation, would allow the estimation of new parameters, in addition to the conventional parameters. Thus, we proposed: 1) new temporal parameters, which were previously described in echocardiography but, to our knowledge, were never assessed in MRI, and 2) new filling flow-related parameters. The automated process, including the segmentations and the parameters extraction, was tested on 25 controls, and results were compared to those previously described in the echocardiographic and MR literature, when available, or were correlated with those known to have a high prognosis value.

2. MATERIALS AND METHODS

2.1. Study population and acquisition protocol

A group of 25 controls (13 men, 12 women, age: 31 ± 10 yrs), without cardiovascular disease, was studied. They had PC imaging using a GE 1.5 Tesla MRI system. For each subject, positioning 2- and 4-chamber views were first acquired. These views allowed positioning a plane, just below the mitral annulus, perpendicular to the mitral inflow. Two dynamic series corresponding to an entire cardiac cycle were acquired in this plane: 1) the transmitral flow sequence (velocity encoding $V_{enc} = 180$ cm/s, Repetition Time = 7.8 ms, Echo Time = 3 ms), and 2) the myocardial longitudinal velocity sequence ($V_{enc} = 15$ cm/s, TR = 9.5 ms, TE = 5 ms). For both sequences, the following parameters were used: flip angle = 20°, slice thickness = 8 mm, pixel spacing = 1.8 x
1.8 mm, matrix 256 x 256. The number of phases per cardiac cycle varied between 43 and 89.

Images were transferred for off-line analysis using a custom software, which allowed a display of velocity images using an adapted color scale, to easily distinguish through-plane velocities in both directions (Figures 1.B and 2.B).

2.2. Automated segmentation of velocity images

2.2.1. Blood flow velocities

Each dataset included dynamic modulus (Figure 1.A) and phase data (Figure 1.B). The modulus images described the mitral annulus motion, resulting in variable shapes, depending on whether the mitral valve was open or close. These images were difficult to segment because of the flow-related temporal contrast variations. We therefore preferred processing velocity images, which presented connected areas, in terms of pixels sign. These areas corresponded to the blood flow, which, in the case of transmitral flow, was directed toward the LV during the filling phase and was therefore perpendicular to the acquisition plane. Based on these connectivity properties, our algorithm comprised the following steps: 1) a rough ROI was manually drawn on a single phase around the flow of interest (Figure 1.B), 2) the biggest connected area, in terms of sign, was automatically detected on this phase and its center of mass was calculated (Figure 1.C), and 3) this center of mass was reported on the neighboring phases and the biggest connected areas containing this point were detected, and their center of mass were used to repeat the process towards the beginning and the end of the cardiac cycle.

![Figure 1: Segmentation of a transmitral flow series A: modulus image, B: diastolic velocity image with the initial ROI, C: result of the segmentation of the image in B, and D: result of the segmentation on selected phases of the cardiac cycle.](image)

The propagation of the center of mass while looking for the biggest connected area constrained the process to avoid segmenting neighboring structures. Curves of maximal and mean velocities, as well as flow rates, were calculated.

2.2.2. Myocardial velocities

Similarly to flow-related data, myocardial data contained a modulus (Figure 2.A) and a velocity-encoded (Figure 2.B) series. Because of the very basal position of the imaging plane, segmentation of myocardial modulus images is even more challenging than segmentation of conventional cine MR images, especially for the epicardial wall (Figure 2.A). Again, velocity images were preferred for segmentation. However, the connectivity process was not adapted because of the bi-directional (up and down) longitudinal motion of the mitral annulus during a single cardiac cycle, which implies changes in velocity sign. Accordingly, a classification based on the c-means algorithm was applied on temporal velocity profiles, within an ROI manually drawn around the LV on a single phase (Figure 2.B). This classification allowed isolating the biggest connected cluster, defined as the “myocardial” cluster (Figure 2.C). This cluster contained pixels remaining within the myocardium during the whole cardiac cycle (Figure 2.D).

![Figure 2: Segmentation of a myocardial series A: modulus image, B: diastolic velocity image with the initial ROI, C: result of the c-means clustering (7 clusters), and D: result of the segmentation on selected phases of the cardiac cycle.](image)

For both blood flow and myocardial segmentations, our software was designed to enable manual corrections if needed. This option was not used in the present study.

2.3. Extraction of functional parameters

Velocity and flow rate (mean velocity * segmented area for each phase) curves were used to extract functional diastolic parameters. The myocardial longitudinal velocity curve, corresponding to the lateral wall (Figure 3.A), was used to derive the parameter Ea. The blood flow curves (Figure 3.B and 3.C) enabled the estimation of conventional parameters, such as E, A and DT. Additional parameters were also estimated: the isovolumetric relaxation time (IVRT), the early peak (Ef, in ml/s) and late peak (Af, in ml/s) filling flow rates and the stroke volume (SV, in ml). The aortic ejection flow, which was visualized on the series used for transmitral flow analysis, was segmented using our method, and the obtained curves provided the end of the ejection needed for the determination of IVRT. The parameters Ef, Af and SV were obtained from the flow rate curves. In addition, flow rate curves were preferred for the estimation of temporal parameters. Indeed, being estimated from the mean velocities, these flow rate curves were, as expected, less noisy than maximal velocity curves.
After manual delineation of structures to be segmented, both flow and myocardial segmentations were achieved automatically on all cardiac phases. Cine displays of the color-coded velocity images, on which the derived segmentation was superimposed, were provided to an independent operator, who visually assessed the efficiency of our segmentation. Both transmitral and aortic flows segmentations were judged satisfactory for all subjects, while the automated segmentation of the mitral annulus was successfully performed in 23/25 subjects. Myocardial PC data of the two remaining subjects had velocity aliasing, which created an additional cluster within the myocardium.

Conventional parameters were averaged over the 25 subjects of our database and presented in Table 1, side by side with values previously described in an echocardiographic study [5] and an MRI [6] studies achieved on controls. Because of the known relation between diastolic parameters and aging [5], we selected studies in which population mean ages were the closest to ours.

The ratio E/Ea, combining transmitral flow and myocardial early peak velocities, obtained in the present study (6.2 ± 2) was within the normal range.

Considering the new parameters, in other words parameters which are estimated with PC MRI for the first time: 1) IVRT mean value was 69 ± 18 ms and compared favorably with value previously described in the echocardiographic study [5] (IVRT = 76 ms (54-98 ms)), 2) comparison of the flow rate parameter Ef/Af (1.8 ± 0.8) and the conventional parameter E/A resulted in a correlation coefficient of r = 0.95 (Figure 4.A), and 3) comparison of the parameter SV/Ef and the conventional parameter DT resulted in a correlation coefficient of r = 0.85 (Figure 4.B).

### Table 1: Comparison of our transmitral flow-related diastolic parameters against those previously described in the literature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present study (n = 25)</th>
<th>Echographic study (n = 61)</th>
<th>MRI study (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>31 ± 10</td>
<td>21-49</td>
<td>33 ± 9</td>
</tr>
<tr>
<td>E (cm/s)</td>
<td>62 ± 17</td>
<td>72 (44-100)</td>
<td>70.6 ± 20</td>
</tr>
<tr>
<td>A (cm/s)</td>
<td>43 ± 7.9</td>
<td>40 (20-60)</td>
<td>45.1 ± 18.8</td>
</tr>
<tr>
<td>E/A</td>
<td>1.5 ± 0.5</td>
<td>1.9 (0.7-3.1)</td>
<td>1.8 ± 0.8</td>
</tr>
<tr>
<td>DT (ms)</td>
<td>177 ± 48.1</td>
<td>179 (139-219)</td>
<td>175 ± 40.7</td>
</tr>
</tbody>
</table>

Figure 4: Comparison between new and conventional parameters.
4. DISCUSSION

Early diagnosis of diastolic dysfunction is crucial for the management and the follow-up of patients with heart failure. In clinical routine, this evaluation is performed using Doppler echocardiography.

MRI is known as the modality of choice for the evaluation of global and systolic LV function, and myocardial viability. However, despite its recent ability to measure velocities through 2D-planes, with high resolutions, using PC imaging, its usefulness for the assessment of diastolic function is not established yet. This limitation is mainly due to technical issues, such as the lack of automated methods designed for the analysis of PC images.

In the present study, we developed a connectivity-based segmentation of blood flow velocity PC images. Our technique required minimal manual intervention, which consisted in positioning a rough ROI around the structure of interest. It was successfully used to delineate both transmitial and aortic flows during the whole cardiac cycle. Thanks to the connectivity basis, our technique is not related to the shape of the flow. This is an important feature because such a technique can be easily used for the segmentation of various flows, such as right ventricular tricuspid flow.

To the best of our knowledge, the segmentation of the mitral annulus was previously presented in only two MRI studies [3, 4] and the placement of the ROI, which provided myocardial velocity curves, was done manually. This manual placement of an ROI on each phase is time-consuming and may lead to inter and intra-observer variability. In our study, the myocardial delimitation was automatically achieved using a c-means clustering algorithm. It was successfully used for all subjects with non-aliased images.

Moreover, a semi-automatic process, which included peaks and foots detection, linear interpolation of ascending and descending waves, and area under curves estimation, was developed to analyze velocity and flow rate curves.

These developments were used to analyze PC data of a study group of 25 controls. This application enabled the estimation of conventional diastolic parameters, which, despite the slight differences in populations age and in afterload conditions, favorably compared with previous echocardiographic and MRI findings, except for the early peak velocity E and the related ratio E/A, which were slightly underestimated in our study, similarly to the results presented by Rubinshtein et al. [7]. Also, new parameters, which by definition are less sensitive to data noise than the commonly-used maximal velocities, were proposed and their comparison to high prognosis conventional parameters resulted in strong correlations. Also, compared to our E/A, the mean Ef/Af over the 25 subjects was closer to the ratio E/A found in the echocardiographic literature (Table 1). This finding might be related to the fact that flow rates are less sensitive to the slight mismatching between the acquisition plane and the real perpendicular to the transmitial flow. Of note, our new parameters being extracted from flow rate curves, their measurement is specific to MRI data. However, a final evaluation of the efficiency of these new parameters should be carried out on a population including pathological subjects.

Although our technique was successfully applied on our database, our study lacks of comparison against echocardiographic measurements. However, since the agreement between the two techniques has already been demonstrated [4], our study focused on the design of new segmentations for both blood flow and myocardial PC data, to overcome the subjective and time-consuming nature of manual contouring. The visual evaluation of this segmentation, as well as the consistency of the derived diastolic parameters with those previously presented in the literature indicated its robustness.

A fast and operator-independent technique was developed and successfully tested on 25 controls, for the automated evaluation of diastolic function from PC MR data. Its addition to MRI tools may prove clinically useful.

5. REFERENCES


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