Automated Assessment of Left Ventricular Wall Motion Based on Surface Detection and Color-Encoding of Real Time Three-Dimensional Echocardiographic Images

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Abstract

Off-line 3D color-encoding was applied to the left ventricular (LV) endocardial surfaces obtained from real-time 3D echocardiographic images. Systolic regional wall motion abnormalities (RWMA) were automatically detected and the accuracy of this method was tested against expert visual interpretation of 2D echocardiographic (2DE) images (apical 2-, 3- and 4-chamber). 20 subjects with normal wall motion (NL), and 14 patients with RWMA were studied. By custom software, color-coded 3D images of systolic wall motion were created, and regional fractional volume change (RFVC) in % of regional end diastolic volume was calculated (18 segments model). In the RWMA pts, RFVCs were compared with thresholds derived from NL subjects for automated classification of the corresponding segments as normal or abnormal. The proposed technique agreed with the expert reader with 91% sensitivity, 80% specificity and 84% accuracy.

1. Introduction

Two-dimensional echocardiography (2DE) allows noninvasive real-time visualization of left ventricular (LV) endocardial motion and wall thickening. Although this imaging modality is the most widely used to evaluate regional LV function, it is based on subjective and experience-dependent visual interpretation of dynamic images of the heart [1-2]. To overcome this limitation, several methods have been proposed for the objective evaluation of regional wall motion. Among them, both on-line [3-4] and off-line [5] color encoding of LV wall motion have been shown to improve visual or automated detection of regional wall motion abnormalities (RWMA).

However, a limitation of the assessment of RWMA by 2DE is that it uses only partial information in specific cross-sectional planes, thus relying on the reader's experience and ability to effectively integrate spatial and temporal information obtained from multiple standard views.

Real-time three-dimensional echocardiographic (RT3DE) imaging potentially overcomes the limitations of 2DE, thus allowing a 3D evaluation of regional ventricular motion from a single dataset. We recently developed a technique for direct 3D semi-automated detection of the endocardial surfaces and quantification of LV volumes from RT3DE datasets [6], and demonstrated that its application throughout the cardiac cycle could be suitable for the objective assessment of RWMA [7].

We hypothesized that color encoding of systolic LV wall motion, applied to the detected endocardial surfaces, could provide the basis for an alternative approach to automatically detect RWMA.

Accordingly, our goals were: 1) to develop an automated technique for off-line 3D color encoding of the detected LV endocardial surfaces 2) to provide an algorithm for automated interpretation of LV regional wall motion; 3) to test its accuracy in detecting RWMA against expert visual interpretation of 2DE images.

2. Methods

20 subjects with normal (NL) wall motion, and 14 patients with RWMA, including 7 with global LV dysfunction, were studied. Transthoracic harmonic RT3DE datasets were acquired in the "full-volume" modality using the SONOS 7500 system (Philips Medical System, Andover, MA) equipped with a fully sampled matrix array transducer (X4). In addition, 2DE images were acquired in apical 2-, 3- and 4-chamber views.

The RT3DE datasets were first analyzed using custom software for semi-automated endocardial surface detection [6], based on the level set approach [8], with the

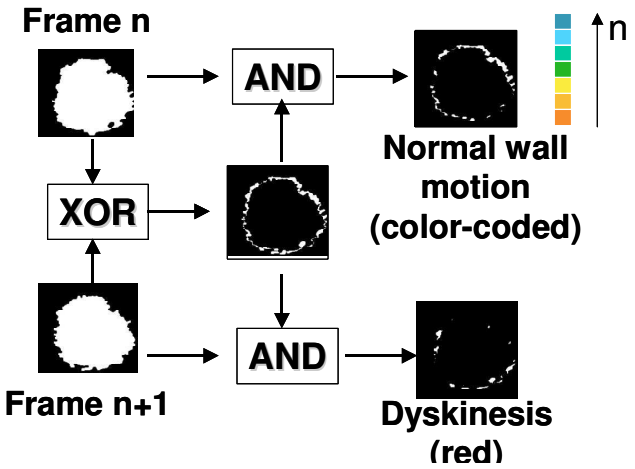

Figure 1. 2D schematization of the color-encoding procedure applied to the detected 3D endocardial surfaces.

papillary muscles included in the LV cavity. This procedure was applied to every consecutive frame, from end-diastole (ED) to end-systole (ES).

2.1. Color-encoding of endocardial motion

For each frame n (n=1, .., ES), starting from the detected LV endocardial surface, a binary 3D representation of the LV cavity was generated, with ones inside and zeros outside. Then, scanning the 3D dataset from the top to the bottom, the apical plane $z_{ap}(n)$ and the base plane $z_b(n)$ were defined as the first and the last 2D planes containing non zero values, respectively. Moreover, the coordinates $(x_c(n), y_c(n), z_c(n))$ of the center of mass of the LV cavity were computed.

A logical "XOR" operation was applied step-by-step to each pair of consecutive frames n and (n+1). This operation resulted in a binary image of only non-overlapping voxels. A logical "AND" operation was performed between this binary image and the frame n, i.e., with the larger LV cavity in each pair, resulting in a binary display of inward endocardial motion. The same logical "AND" operation, when applied to the frame (n+1), containing the smaller LV cavity in each pair, was used to display paradoxical (outward) endocardial motion (Figure 1). Subsequently, a composite color-encoded 3D image K of systolic endocardial motion was created by combining data obtained from each pair of frames (Figure 2). Voxels reflecting inward endocardial motion were assigned different colors depending on the frame number, i.e. the timing of motion in the cardiac cycle. Red color was assigned to voxels where only paradoxical (dyskinetic) wall motion was detected.

Moreover, for visualization purposes, a color-coded RT3DE dataset was generated by substituting for each frame (from n+1 to the ES frame) the original voxel values with the corresponding color value.

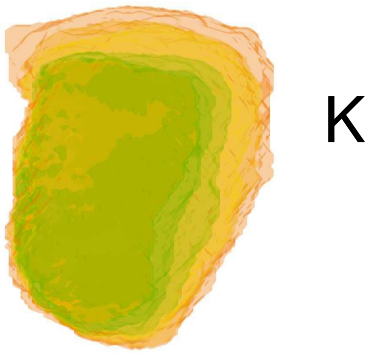

Figure 2. Example of the color-encoded 3D image K of systolic endocardial motion, created by combining data obtained from each pair of frames (outer surface: end-diastole; inner surface: end-systole).

2.2. Quantitative analysis of regional LV wall motion

To focus on the radial inward motion only (Figure 3), thus excluding from the analysis the confounding effects of the longitudinal motion of the LV apex and base, a volume of interest V was defined starting from:

$$Z_{start} = \max(z_{ap}(1), .., z_{ap}(ES))$$

and ending at:

$$Z_{end} = \min(z_b(1), .., z_b(ES)).$$

Then, the volume V was divided in longitudinal direction into 3 equally spaced subvolumes, with $\Delta z = (Z_{end} - Z_{start})/3$:

$$\text{Zapex: } Z_{start} \le z < Z_{start}+\Delta z$$
$$\text{Zmid: } Z_{start}+\Delta z \le z < Z_{start}+2\Delta z$$
$$\text{Zbase: } Z_{start}+2\Delta z \le z < Z_{end}$$

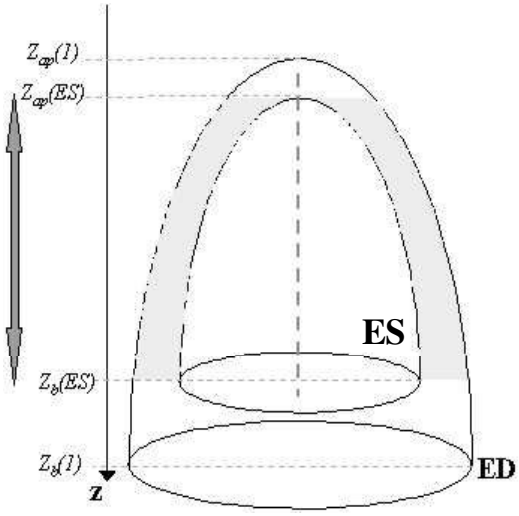

Figure 3. Schematization of the volume of interest V (in gray) in which the quantification of LV wall motion will be performed, to exclude longitudinal motion from the analysis.

A manually determined anatomic landmark M, representing the junction between the right ventricular free wall and the inter-ventricular septum, was selected on the ED frame at the level of the center of mass $z_c(1)$.

For each z included in V, the center of mass of the LV cavity area in the x-y plane was computed and used together with M to define the zero degree line of the segmentation. Starting from these points, the angular positions of six 60° wedge-shaped sectors (i.e., anterior, antero-septal, septal, inferior, posterior and lateral), corresponding to the standard segmentation scheme of the LV short axis view used for visual assessment and grading of wall motion [9], were defined.

This segmentation scheme resulted in the definition of 18 different segments (3 levels on the z coordinate * 6 sectors on the x-y plane), which were applied to the color-encoded 3D image K for the quantification of the 3D wall motion. In correspondence to each segment, the voxels of each color in K, representing the incremental volume change occurring between two specific consecutive frames, were counted. For each segment, the regional fractional volume change (RFVC) was automatically computed as the total number of colored voxel (excluding dyskinetic red voxels, counted apart), and expressed in % of regional ED volume (RFVC%). This resulted in the display of three stacked color histograms [4], relevant to the Zapex, Zmid and Zbase.

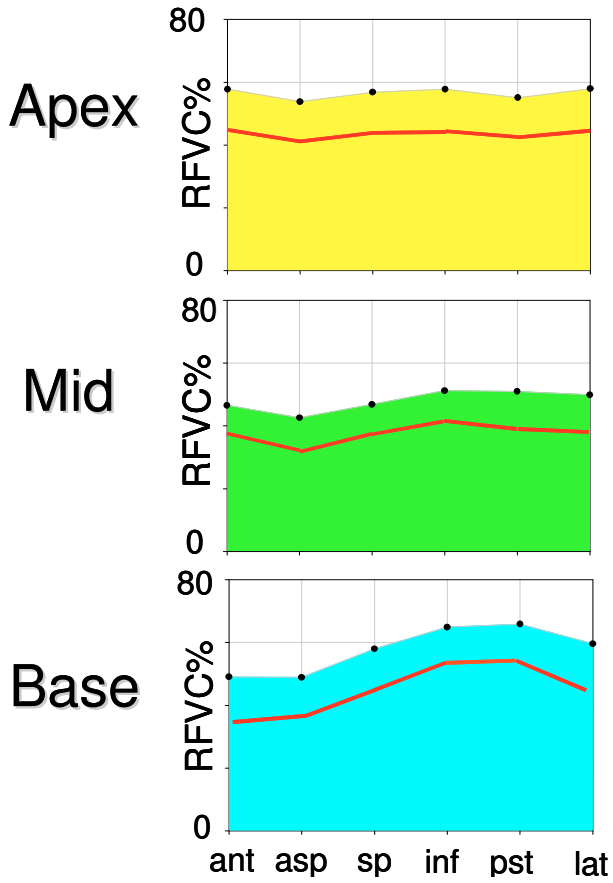

Figure 4. Mean regional fractional volumes in % of regional end-diastolic volumes (RFVC%) computed in the 20 NL, and used to obtain the optimal threshold (bold line) as mean-0.8*SD, for the automated interpretation of wall motion.

2.3. Automated interpretation of LV wall motion

RT3DE datasets obtained in the 20 NL subjects were analyzed in order to define the regional threshold values for RFVC% for automated interpretation of LV wall motion. For each of the 18 segments, the mean RFVC% minus 0.8SD, optimized using receiver operating characteristic analysis, was used as the regional threshold for automated classification of each segment, and applied to the automated interpretation of LV wall motion as normal (RFVC% ≥threshold) or abnormal (RFVC% <threshold) in the 14 RWMA patients.

The 2DE images (apical 2-, 3- and 4-chamber) obtained in the 14 RWMA patients were reviewed by an expert cardiologist, who graded wall motion in each segment (18 segments model) as normal or abnormal.

The performance of our algorithm for detecting RWMA was compared to the gold standard expert interpretation by counting the segments where concordant (true positive and negative) as well as discordant (false positive and negative) readings were made. Segment counts were used to calculate the sensitivity, specificity, and overall accuracy of the automated interpretation of regional wall motion.

3. Results

Once the LV endocardial surfaces were available, and the anatomic landmark required for segmentation was set, the generation of the 3D color-encoded dataset and the automated interpretation of regional wall-motion took less than 5 sec/patient.

Figure 4 shows the mean RFVC% values obtained in the 20 NL subjects at apical, mid and base levels of the LV, with the corresponding normal reference curves (i.e., threshold = mean-0.8SD) below. These curves evidenced regional differences in the normal values among the segments. In particular, lower mean RFVC% values in the anterior and antero-septal wall were found in the LV base, consistent with the reduced mobility of the basal LV segments adjacent to the aortic outflow tract.

Of 252 segments examined in the RWMA patients, according to the gold standard interpretation, 182 (72%) were graded as abnormal and 70 as normal (28%). The automated technique agreed with the expert reader in 225 (192 true positive and 33 true negative) segments (89%),

with only 8 (3%) false positive and 19 (8%) false negative detections, thus resulting in 91% sensitivity; 80% specificity and 84% accuracy.

4. Discussion and conclusions

Clinical assessment of LV wall motion is mostly based on visual interpretation of dynamic ultrasound 2D images. This methodology heavily relies on the reader's ability to efficiently extract and integrate spatial and temporal information on endocardial motion and wall thickening, which requires extensive training and is known to be subjective and experience dependent [1-2].

By exploiting the whole 3D information about LV wall motion, RT3DE has the potential to be utilized for the evaluation of global and regional LV function. We previously demonstrated that semi-automated endocardial surface detection [6] applied frame-by-frame throughout the cardiac cycle provides reliable measurements of LV volume, when compared with reference magnetic resonance imaging, and could be used for the automated detection of RWMA [7]. In this study, we aimed to improve our previous findings in several ways: 1) by providing a tool for visualization of wall motion information, by off-line 3D color encoding of the detected LV endocardial surfaces; 2) by introducing a new segmentation scheme, which aimed to exclude the potential confounding effects of longitudinal motion from the automated evaluation; 3) by quantifying both kinetic RFVC%, as cumulative colored voxel counts, and dyskinetic volume, as red voxel counts; 4) by increasing the number of subjects with normal wall motion for the definition of the regional normality thresholds.

This resulted in a slight improvement in the agreement of automated interpretation of LV wall motion (89%) with the expert reading, compared to our previously reported results (86% [7]). We believe that the introduction of the regional dyskinetic volume as an additional criterion to discriminate between normal and abnormal wall motion, would further improve the reliability of the automated assessment of LV wall motion. Albeit in a small group of patients, the ability to automatically detect RWMA was proved in our protocol, which was aimed at establishing the clinical usefulness of segmental analysis of RT3DE data in patients with RWMA, once the 3D LV endocardial segmentation is available.

A potential limitation of our study is the temporal resolution of the RT3DE images, which is lower (around 15Hz) and thus does not allow to fully exploit the information relevant to the timing of the cardiac contraction. Moreover, due to the simple quantification scheme, which requires the identification of one anatomical landmark only, the RT3DE has to be acquired to contain the LV with its long-axis parallel to the Cartesian z-axis. If this condition is not verified, the detected endocardial surfaces could need to be realigned before the application of the proposed procedure.In conclusion, we found that off-line color-encoding of LV endocardial motion provides the basis for automated quantitative assessment of regional LV function. Moreover, the proposed technique, when used in conjunction with conventional visual assessment of wall-motion from RT3DE images, could improve the objective detection of RWMA.

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