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Sequential functional analysis of left ventricle from 2D-echocardiography images

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The sequential changes in shape of left ventricle (LV), which are the result of cellular interactions and their levels of organizational complexity, in its long axis view during one cardiac cycle are obtained. The changes are presented in terms of shape descriptors by processing of images obtained from a normal subject and two patients with dilated left ventricular cardio-myopathy. These images are processed, frame by frame, by a semi-automatic algorithm developed by MATLAB. This is consisting of gray scale conversion, the LV contour extraction by application of median and SRAD filters, and morphological operations. By filling the identified region with pixels and number of pixels along its contour the area and perimeter are calculated, respectively. From these the changes in LV volume and shape index are calculated. Based on these the stroke volume (SV) and ejection fraction (EF) are calculated. The changes in LV area, perimeter, volume and shape index in cardiac patients are less than that of normal subject. The calculated SV and EF of normal subject are within the range as obtained by various imaging procedures.

Keywords: Algorithm, Cardiomyopathy, 2D-echocardiography, Left ventricle, Shape descriptors

The left ventricle (LV) and in particular the endocardium is a structure of particular interest since it performs the task of pumping oxygenated blood to entire body[1]**.** During this the LV undergoes various shape transformations which primarily depend on ability of deformation of its structural elements. The amount of blood which is pumped into aorta during each cardiac cycle, referred to as stroke volume (SV), depends on the change produced in LV volume. Thus the change in shape of left ventricle is an important diagnostic and therapeutic index for evaluation of variety of cardiac states.

Echocardiography is a non-invasive, low cost and radiation-free imaging technique, which has extensively been used for qualitative functional analysis of LV in wide range of cardiac diseases[2,3]. The procedures applied for LV volume calculation include two-dimensional multiple echo views[4], Doppler echocardiography[5], and 3D-echocardiography[6]. The change in shape of the LV is determined by application of image processing procedures[2,7,8]. Further development includes the semi-automatic procedure which has helped in speedy processing of images[1]. But for the assessment of the LV performance over a cardiac cycle, in terms of shape descriptors, these images are to be further processed. Recently Lacerda, *et al.*[2], by applying the conventional image processing procedures combined with radial search method determined the change in LV area from maximum to minimum during diastole to systole of cardiac cycle, respectively. The perimeter of the LV combined with area is further applied to calculate the shape index (a parameter which is related to deviation from a circular shape[7]) and its volume[9]. The physiological parameters such as stroke volume and ejection fraction for clinical assessment of LV are required. These are generally obtained by advanced echocardiography systems[4,5,6,10]. In contrast to such elaborate procedures these vital parameters can be calculated from the variation of shape descriptors of LV, as obtained by processing the sequence of images obtained during a cardiac cycle by a low cost 2D-echocardiography system. For this purpose an efficient semi-automatic algorithm to calculate the area and perimeter is required. Based on these the shape index and volume, and finally stroke volume and ejection fraction are calculated. Such a procedure to the best of our knowledge is not reported. This forms the objective of

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the present work, which not only shows the changes in LV parameters in healthy subject but also their variation in cardiac patients.

Materials and Methods

Subjects and data acquisition—This study includes one normal subject and two patients with dilated left ventricular cardio-myopathy. 2D-Echocardiography images of heart were taken by Philips echocardiography system (HDI1500, Canada), functioning at 5.0 MHz in B-mode scan with 3 lead ECG as a marker of cardiac functioning. For normal subject video, each sequence was recorded for two cardiac cycles in apical 4 chamber long axis view at a rate of 15 frame/s and of size 600×800 pixels with an audio-video-interleave (AVI) file format. For patients each sequence in the same view and frame rate for three cardiac cycles was recorded. Prior to each recording the consent of each subject was obtained.

Image processing algorithm—For further processing the echocardiography data were stored in the computer. The images by using image processing Toolbox in Matlab R2010a were processed. Brief description of each operation of the algorithm (Fig. 1), applied to process the images, is given below:

Extraction of frames: The frames were extracted from video by using MATLAB command.

Cropping of LV portion: The first frame, the relaxed phase of left ventricle as marked by ECG, with maximum area, was taken and by cropping this part alone was focused. This automatically cropped portion was applied to all other frames.

Median filtering: To remove noise from gray-scale images and for smoothening, the median filter of size 3×3 was applied[11].

SRAD filter: Speckle reducing anisotropic diffusion (SRAD) filter[12] was applied on to the median filtered image which not only retains the important information of object boundaries of related structures but also enhances the morphological definition by sharpening discontinuities[13].

LOG filter: In order to identify the border points from structures present in the image the LOG (Laplacian of Gaussian) filter of size (3×3) was applied[14]. By this operation the regions of rapid intensity change in images were highlighted and were used for edge detection.

Morphological opening: This operation breaks thin connections and removes thin protrusions and smoothen object contour[11].

Morphological closing: For obtaining the gaps-free boundary of LV the closing operation was performed. By this a smooth contour was obtained[11].

Morphological erosion: This operation shrinks or thins the outer boundary of contours[11]. Finally the left ventricular contour of one pixel thickness was obtained.

Binary conversion: Gray scale filtered image was converted to binary image.

Region filling: The region of interest was filled with value 1 assigning to each pixel inside the object[15]. By this procedure the extraction of LV contour was performed and this processing was automatically applied to all frames.

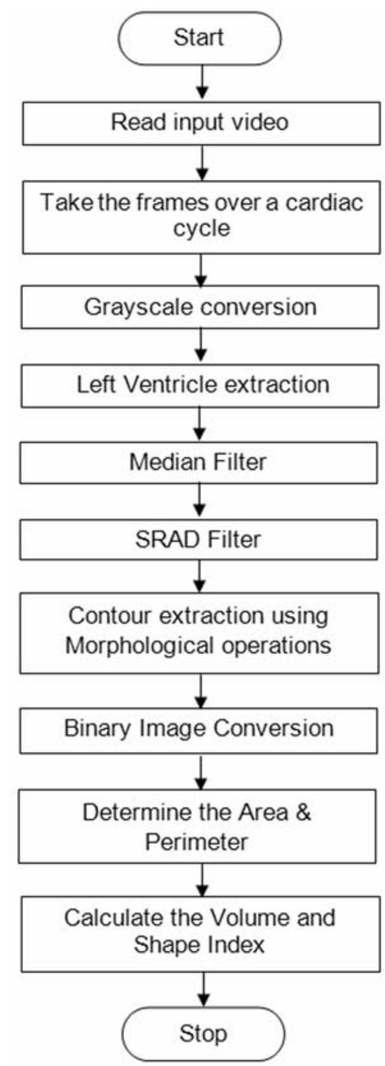

Fig. 1—Algorithm applied on to the sequence of images for extraction of contour of LV for area and perimeter measurement.

Calculation of shape descriptors—The four descriptors, area, perimeter, volume and shape index of the left ventricle over the complete cardiac cycle were calculated. For comparison purpose three cardiac events were selected. These are isovolumetric contraction, isovolumetric relaxation of LV, and atrial systole as represented in figures 3 to 6 by 1, 2 and 3, respectively[15,16].

Area of left ventricle: For calculation of area, the number of pixels inside the contour was taken and multiplied with area of each pixel[16]. Based on the area at various intervals of cardiac cycle its variation with time was plotted.

Perimeter of left ventricle: For calculation of perimeter, the number of pixels along the contour was taken and was multiplied by the length of each pixel[16]. From this data the perimeter variation with time, during cardiac cycle, was plotted.

Volume of left ventricle: This is an important 3-D parameter calculated from area by the following formula:

$$V_{estimated} = \frac{8A^2}{3\pi A^{1/2}}$$ [9].

Based on this data the volume changes of LV during one cardiac cycle were plotted.

Left ventricle shape index—This parameter is sensitive to deviation of shape from a circular one and was depending on area and perimeter of the contour. The shape index calculated by $4\pi(Area)/(Perimeter)^2$ was plotted at various time intervals of cardiac cycle[9].

Left ventricle stroke volume—This is a parameter directly related to cardiac performance. From the volume variation graph the LV stroke volume, by taking the difference between the end-diastolic volume (EDV) and the end-systolic volume (ESV), which corresponded to the maximum and minimum values, respectively, was calculated[10].

Calculation of ejection fraction (EF) —The EF, given by ESV divided by end diastolic volume (EDV), was calculated[10].

Results

Figure 2 shows the raw input images and the processed ones of normal subject and of patients with cardiac diseases obtained in long axis view, respectively. The processed region is limited to the LV which is highlighted in these figures. The noisy pixels, due to papillary muscles and blood inside the LV chamber, are removed.

Figure 3 shows the variation of area and perimeter of the LV at various intervals of cardiac cycle. The LV area in normal subject in isovolumetric relaxation phase (phase 2) is less than half compared to isovolumetric contraction phase (phase 1), whereas, this change is approximately 25% in patients. The area is more in patients throughout the cardiac cycle.

The variation in perimeter during various time intervals of cardiac cycle is shown in Fig. 4. Throughout the cardiac cycle the perimeter of normal subject is less than that of patients. In contrast to area, there is patient to patient variation in perimeter, indicating the change of shape of heart in patients. The change in perimeter at cardiac events 1, 2 and 3 shows respective variation in normal and cardiac patients during the cardiac cycle. Figure 5 shows the variation of the derived parameter volume during a cardiac cycle. Similar to area, the change in volume is more in normal subject compared to that in patients. In all subjects the minimum volume is observed during the phase 2. The lesser change during phase 2 compared to 1 or 3 indicates that the normal functioning of the LV in patients is impaired.

Figure 6 shows the variation in shape index (SI) during a cardiac cycle in comparison with that of a circular shape (SI=1). During the phase 2 this parameter for normal LV is 1.25, showing lesser deviation from circular shape compared to that of patients with shape index variation from 2.0 to 2.4.

The comparison of derived parameters SV and EF of normal and patients is shown in Table 1. In cardiac patients these are less than half compared to that of normal subject, indicating the weakness in contractile mechanism of the LV. The calculated values of SV and EF of normal subject are compared with that as obtained by using MRI, 2D-echocardiography and radiological procedures[1,17,18]. The values obtained for normal LV by this procedure are within the range of variation as obtained by other procedures.

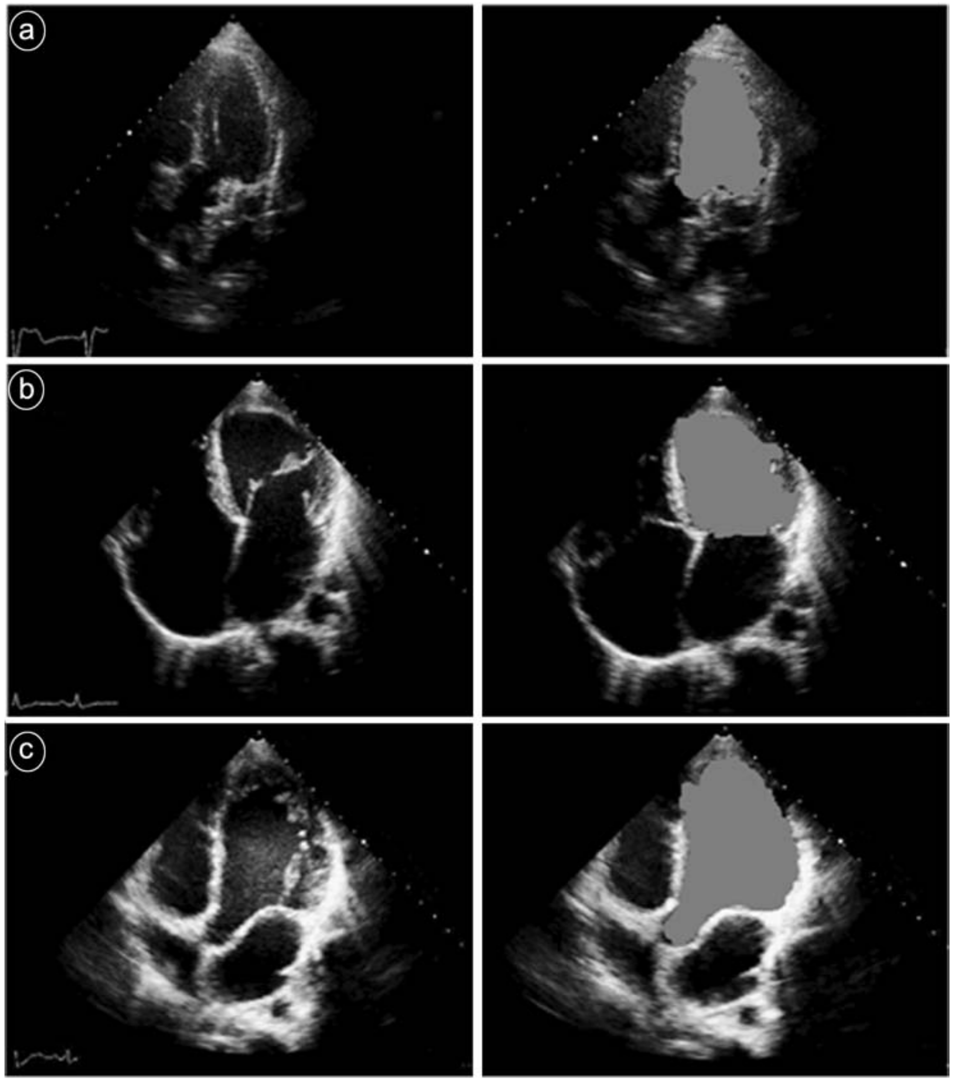

Fig. 2—Input images in long axis four chamber view (left panel) and the processed left ventricle area (right panel) of (a) normal subject, (b) cardiac patient 1 and (c) cardiac patient 2.

Discussion

Biological shape of any tissue structure is the result of endogenous and exogenous mechanisms that operate at different scales of space and time and levels of organizational complexity. Endogenous mechanisms include molecular signaling between epithelial and mesenchymal cells and interactions between gene products that control gene expression and cell movement in the extracellular environment[19]. The description and measurement of biological shape are therefore of fundamental importance to assess various changes.

The functional analysis of the left ventricle is vital for the human body in health and cardiac diseases. The present work is based on the application of an algorithm to calculate shape descriptors from the processed 2D-echocardiography images. These descriptors are mathematical functions which are applied to an image and produce numerical values which are representative of a particular characteristic of the tissue. The images of the biological tissues are generally obtained by various techniques and are processed. This procedure was applied to microscope images of erythrocytes and their formed aggregates to show the changes induced by malaria parasites at various stages of parasitemia[16].

The present work shows the variability of the shape-related parameters. The changes observed in area of LV during a cardiac cycle are more in healthy subject compared to that in patients. The perimeter also decreases during cardiac cycle but this change is less compared to that of area. The various shapes taken up by left ventricle during entire cardiac cycle in normal subject, as shown by the variation in shape index, are more than that in cardiac patients. This is attributed to the cardiomyopathy which has produced the functional changes in LV in patients.

Left ventricular volume is an important clinical indicator for the diagnosis and the monitoring of treatment in many heart diseases. The various invasive procedures which have been applied for determination of volume of LV include X-ray angiography, 3D reconstructed image from CT slices[10], and single photon emission computed tomography (SPECT)[20]. Cardiac magnetic resonance imaging (MRI) is an expensive technique as the

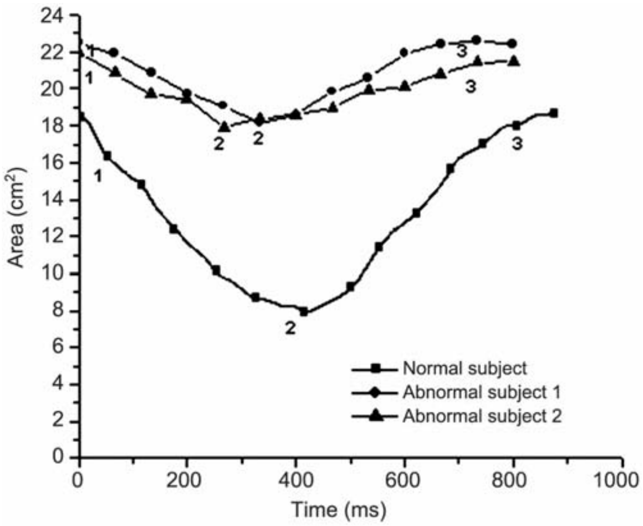

Fig. 3—Change in area of left ventricular cavity in normal subject and patient with dilated cardiomyopathy in one cardiac cycle. The cardiac events shown by 1, 2 and 3 refer to isovolumetric contraction, isovolumetric relaxation and atrial systole, respectively.

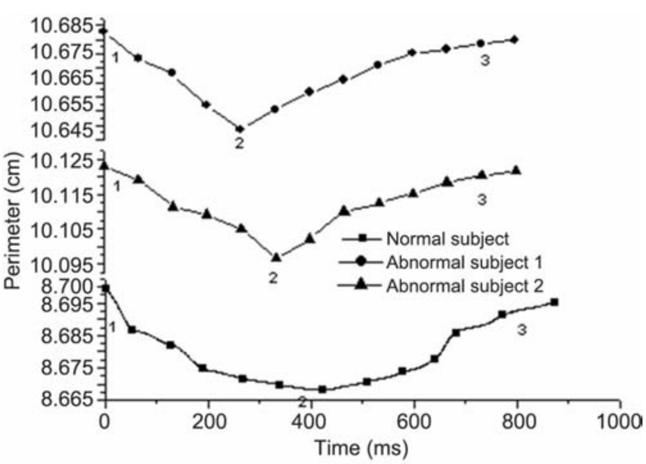

Fig. 4—Left ventricular cavity perimeter changes in normal subject and patient with dilated cardiomyopathy in one cardiac cycle. The various events, as shown by 1, 2 and 3, show their respective variation during cardiac cycle.

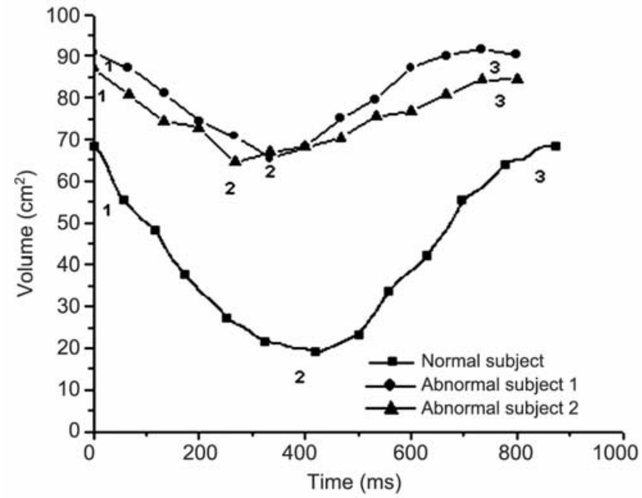

Fig. 5—Change in volume of left ventricular cavity in normal subject and patients in one cardiac cycle. The various cardiac events, as shown by 1, 2 and 3, show their respective variations.

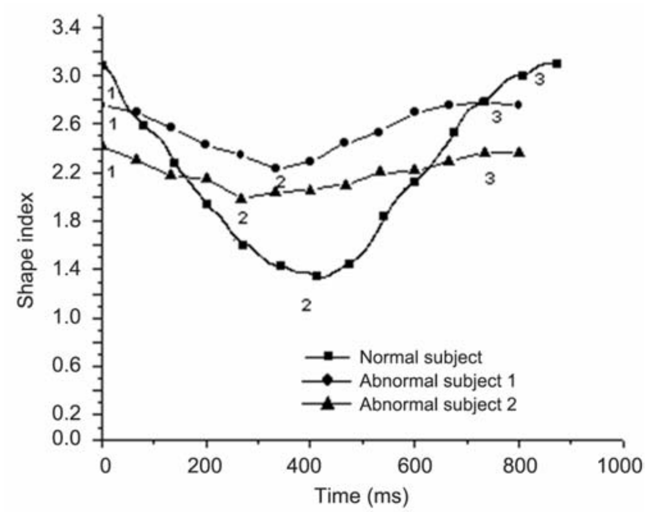

Fig. 6—Changes in left ventricular cavity shape index in normal subject and patients in one cardiac cycle. There are more changes in shape in normal subject compared to that of patients. A patient to patient variation in this parameter is also observed.

Table 1—Comparison of cardiac parameters for normal and dilated hearts

Parameter	Normal	Patient 1	Patient 2	Normal values given by others
Stroke Volume (mL)	50.8	22.5	20.1	45±13.0 (refs.1,17)
Ejection Fraction (%)	0.73	0.248	0.231	0.67±0.08 (refs.1,18)

morphological and functional analysis of LV depends on its reconstruction by cardiac slices in the long axis[18]. By our non-invasive procedure the volume changes over a cardiac cycle are determined. The percentage change in volume of LV during a cardiac cycle in patients is less than the healthy subject which shows the changes induced by cardiomyopathy in the functioning of heart. The volume changes in combination with shape analysis of LV may further provide a more comprehensive assessment of left ventricular performance[21].

Further comparison of parameters between normal subject and patients show that due to weakness in contraction mechanism the SV is reduced to less than 50% of the normal subject. The EF in patients is reduced to 35% approximately of its normal value, which confirms that the patients are suffering from LV cardiomyopathy[22]. The comparison of the SV and EF of normal subject, as calculated by the present procedure, are within the range as obtained by other radiological procedures[1,17,18]. Left ventricular dilation is the abnormal condition of the heart associated with its enlargement and weakness, leading to its reduction in pumping capacity. The observed variations in SV and EF are attributed to these changes.

In conclusion, the present algorithm used in processing of the LV images provides data of normal subjects which is comparable to that as obtained by other procedures. In contrast to other procedures, this method provides the data on the variability of four parameters which are used to calculate important physiological parameters. This procedure is less expensive as this could directly be used to quantify various vital LV parameters from the 2D echocardiography images required for detection of cardiac abnormalities, The application of signature analysis on to observed contours can further help in identifying the affected regions of the LV[9,23].

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