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Three-dimensional analysis of regional left ventricular endocardial curvature from cardiac magnetic resonance images

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Abstract

Purpose: Left ventricular (LV) remodeling is usually assessed using global changes in LV volume. We hypothesized that three-dimensional analysis of regional endocardial curvature from magnetic resonance images could provide clinically useful information on localized LV remodeling. We tested this approach by investigating regional differences in endocardial curvature in normal and hypokinetic ventricles.

Materials and Methods: Images were obtained in 44 patients with normal LV function (NL, N=14), dilated cardiomyopathy (DCM, N=15) or ischemic heart disease (IHD, N=15). Local surface curvedness, normalized to take into account instantaneous LV size (C_n), was calculated throughout the cardiac cycle and compared between segment groups: NL (N=401), IHD (N=92) and DCM (N=255).

Results: In all normal segments, C_n gradually increased during systole and then decreased during diastole. While both maximum and minimum values of C_n were comparable in the basal and midventricular segments, they were significantly higher in the four apical segments and highest in the apical cap. In addition, percent change in C_n was higher in mid and apical compared to basal segments (P<.05). At all LV levels, C_n values in DCM segments were lower (P<.05) than in NL and IHD segments, which were similar. In contrast, percent change in C_n was significantly lower in both IHD and DCM segments compared to NL.

Conclusion: Three-dimensional analysis of LV endocardial curvature yielded quantitative information on regional ventricular shape consistent with the known pathophysiology, supporting its potential clinical usefulness in the evaluation of LV remodeling.

Keywords: Cardiac magnetic resonance imaging; Left ventricle; Three-dimensional analysis; Endocardial curvature; Endocardial curvedness

1. Introduction

Left ventricular (LV) remodeling as a result of disease progression or in response to therapy is reflected by changes in ventricular size and shape, which may be independent of each other. Nevertheless, to date, quantitative assessment of LV remodeling has been predominantly described in terms of changes in LV volume and ejection fraction, while disregarding the simultaneously occurring changes in ventricular shape. While a variety of techniques for quantitative evaluation of LV volume have become part of standard clinical practice [1–3], the development of tools for quantitative evaluation of ventricular shape has been explored only partially [4–7]. This is despite several studies indicating that LV shape analysis may be potentially useful and could be used in conjunction with different imaging modalities, including radionuclide ventriculography [8,9], electron beam computed tomography [10] and ultrasound images [11–14]. Moreover, LV function has been studied both on a global and regional basis, but previous studies have focused on global LV shape, while only initial feasibility data have been published regarding local LV shape [14,15]. A new technique was recently proposed for global LV shape analysis from real-time three-dimensional (3D) echocardiographic images [16], which was able to demonstrate independent changes in LV volume and shape as well as to identify differences between normal and abnormal ventricles.

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In the current study, we focused on the quantification of regional endocardial curvature from dynamic 3D LV endocardial surfaces derived from cardiac magnetic resonance (CMR) images with the rationale that such analysis could prove useful in the evaluation of LV remodeling. Initial testing of curvature analysis in a small number of patients from CMR images [17,18] had demonstrated its feasibility and yielded promising results that warrant further testing and validation in larger groups of patients. Accordingly, the aims of this study were (a) to determine normal patterns of regional endocardial curvature and its changes throughout the cardiac cycle by analyzing CMR images obtained in patients with normal LV wall motion and (b) to test this technique on images obtained in patients with global and regional hypokinesis, in order to understand the effects of these conditions on regional LV shape.

2. Methods

2.1. Population

We studied 44 consecutive patients referred for CMR imaging, including 14 patients with normal to mildly abnormal LV function (NL group), 15 patients with regional wall motion abnormalities secondary to ischemic heart disease (IHD group) and 15 patients with idiopathic dilated cardiomyopathy (DCM group). Clinical characteristic of the study population are summarized in Table 1. Exclusion criteria were dyspnea precluding a 5- to 10-s breath-hold, atrial fibrillation or other cardiac arrhythmias, pacemaker or defibrillator implantation, claustrophobia and other known contraindications to CMR imaging. The protocol was approved by the Institutional Review Board, and written informed consent was obtained in all patients.

2.2. Image acquisition

Cardiac magnetic resonance images were obtained using a 1.5-T scanner (Siemens, MAGNETOM Sonata, Erlangen, Germany) with a phased-array cardiac coil. Electrocardiogram-gated localizing spin-echo sequences were used to identify the long axis of the heart. Steady-state free precession (true FISP) dynamic gradient-echo mode was then used to acquire images using retrospective electrocardiographic gating and parallel imaging techniques (mSENSE) during 5- to 10-s breath-holds with a temporal resolution of 30 frames per cardiac cycle. Cine-loops of 8-mm-thick slices with 2-mm gaps and 2.0×2.0-mm in-plane spatial resolution were acquired in several planes. First, three long-axis planes representing the two-, three- and four-chamber views were acquired. Subsequently, a stack of short-axis views was obtained from just above the ventricular base to just below the apex. All images were stored digitally for off-line analysis.

Table 1
Clinical characteristics of the study group subdivided NL, IHD and DCM

	NL	IHD	DCM
n	14	15	15
Gender (M/F)	10/4	10/5	6/9
Age (years)	51±18	63±11	55±14
Segments with normal/abnormal wall motion	238/0	163/92	0/255
LV EDV (ml)	158±44	195±45	260±69
LV ESV (ml)	74±34	128±41	197±75
LV EF (%)	54±10	35±9	26±11

EDV: end-diastolic volume; ESV: end-systolic volume; EF: ejection fraction.

2.3. 3D endocardial surface detection

The entire set of short- and long-axis images was analyzed using prototype software (4D-LV Analysis MR, TomTec Imaging Systems, Unterschleissheim, Germany), as depicted in Fig. 1. End-diastole was identified as the first frame in the sequence and end-systole as the frame depicting the smallest LV cavity. For each of these two frames, LV endocardial boundary was manually initialized in each of the three long-axis views, while including the papillary muscles and endocardial trabeculae in the LV cavity (Fig. 1, top panels). Then, the endocardial surface was reconstructed by finding the best fit to the endocardial boundaries throughout the cardiac cycle. Subsequently, the reconstructed surface was superimposed on the original image set, and its position was adjusted frame-by-frame by an experienced investigator wherever the surface did not accurately follow the endocardium. Finally, temporal smoothing was performed to avoid temporal discontinuities. The resultant dynamic endocardial surface (Fig. 1, bottom) was exported as a connected mesh for custom analysis of LV endocardial curvature.

2.4. 3D curvature analysis

Custom software was used for analysis of regional LV endocardial curvature, as schematically depicted in Fig. 2. First, for each node on the connected mesh representing the LV endocardial surface (Fig. 2, left), a quadric polynomial function was locally fitted to approximate a smooth surface using a robust method previously described elsewhere [19]. Then, for each point, two values were calculated: maximum curvature k_1, defined as the inverse of the radius of the smallest circle that would fit into the surface at that particular point, and the curvature k_2, similarly defined in the perpendicular direction (Fig. 2, middle). Then, local 3D surface curvedness, C, was calculated as the root mean square value of k_1 and k_2 (Fig. 2, right) [20] and then normalized by mean instantaneous LV curvedness, calculated by averaging curvedness at all nodes on the endocardial surface. This latter step was performed to compensate for changes in LV regional shape secondary to changes in LV size. Theoretically, if the ventricle were a perfect sphere contracting symmetrically, then regional curvedness everywhere would be the same as the mean curvedness calculated from the volume, and the ratio would be 1 at all times. Thus,