Original Paper

Mechanical Evaluation of Human Heart Wall Motion Using Magnetic Resonance Tagging Technique

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Abstract

The cardiac contractility in human heart was investigated by analyzing deformation of the left ventricular wall during systole using a magnetic resonance tagging technique. Subjects were ten normal humans, eight patients with a hypertrophic cardiomyopathy (HCM), and seven patients with a hypertensive heart disease (HHD). The circumferential strain at a short-axis section was employed as an index for an evaluation of the cardiac contractility. The obtained results showed that the circumferential strains in local regions of the patients with a HCM were significantly smaller compared with those in corresponding regions of the normal humans, while the circumferential strains of the patients with a HHD were similar to those of the normal humans in whole regions. This study may suggest that the circumferential strain could be an effective index for the quantitative evaluation of the cardiac contractility.

Key Words: Biomechanics, Magnetic Resonance Tagging Technique, Human Left Ventricle, Myocardial Wall Motion, Circumferential Strain, Cardiac Contractility, Cardiac Disease

1. Introduction

Hearts, especially left ventricles, play a role as an ejection pump in the circulatory system, and ejection of blood is caused by contraction of the myocardium. It is, therefore, considered that to evaluate the cardiac contractility from a mechanical point of view by analyzing the deformation behavior of the myocardial wall is useful for a quantitative evaluation of the extent of heart disease or the effect of treatment. In order to analyze the deformation of the myocardial wall in humans, a noninvasive measurement of regional wall motion is required. A magnetic resonance tagging technique[1-3] is one of such measurement techniques. By applying this technique, the state of nuclear spins at specific locations in an imaging object is modified spatially, so that

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patterns of stripes can be formed in the imaging object. The tagging stripes move together with motion of the imaging object. As a result, imaging a heart using the magnetic resonance tagging technique and tracking the movement of the tagging stripes within the myocardial wall are enable the noninvasive measurement and analysis of the human myocardial wall motion and deformation[4-9].

From the above-mentioned point of view, we have tried to investigate mechanically the cardiac contractility by using the magnetic resonance tagging technique[7-9]. In previous papers[7,8], the two-dimensional deformations of the left ventricular walls during ejection period in normal humans and a patient with a hypertrophic cardiomyopathy were analyzed. Then, we discussed that what kind of physical quantities was important to evaluate quantitatively the cardiac contractility. The obtained results suggested that the strain, which describes the pure deformation, could be an important and effective index for the evaluation of the cardiac contractility from viewpoints of both the physical meaning of this parameter and the ability to detect a singular region in the diseased heart. In the present paper, by applying this strain analysis method to patients with a hypertrophic cardiomyopathy and to patients with a hypertensive heart disease, the cardiac contractility in each heart disease is investigated from a mechanical point of view, and usefulness of the mechanical evaluation of the cardiac contractility is discussed.

2. Image Acquisition

Ten normal humans (6 men and 4 women, aged 21-56 years), eight patients with a hypertrophic cardiomyopathy (HCM, 6 men and 2 women, aged 21-62 years), and seven patients with a hypertensive heart disease (HHD, 7 men, aged 39-69 years) were imaged with a 1.5 T superconducting magnet (SIGNA advantage, GEMS). The imaging procedure to obtain left ventricular short-axis images is as follows;

(1) Coronal gradient-echo images are obtained to identify a cardiac location.

(2) An oblique gradient-echo image is obtained so as to pass through the center of the aortic root and the left ventricular apex, as seen in the coronal image traversed the largest left ventricular cavity.

(3) A left ventricular long-axis is chosen so as to pass through the center of the mitral orifice and the apex, as seen in the oblique image.

(4) Multiphase tagged short-axis images at an equatorial section of left ventricle perpendicular to the chosen long-axis are obtained under the conditions of image acquisition as follows; 28 cm field of view, 256×256 image matrix, 10 mm thickness, and 7 mm tagging stripe spacing.

The first tagged image is assumed to correspond to that at end diastole, because the first image is obtained after 20 ms from detection of the R wave of the electrocardiogram, and subsequent tagged images are obtained continuously at intervals of 25 ms.

3. Deformation Analysis

Tagging stripes form a number of intersections within the myocardial wall, and these intersections serve as material points in the myocardial wall. The deformation of the left ventricular wall was analyzed by tracking the intersections of the tagging stripes throughout systole. The components of Green's strain tensor E_{xx}, E_{xy}, and E_{yy} within a triangular region defined by three adjoining intersections were calculated by

$$\begin{aligned}
\left(ds_1^2 - dS_1^2\right)/2 &= E_{xx}dX_1^2 + 2E_{xy}dX_1dY_1 + E_{yy}dY_1^2 \\
\left(ds_2^2 - dS_2^2\right)/2 &= E_{xx}dX_2^2 + 2E_{xy}dX_2dY_2 + E_{yy}dY_2^2 \\
\left(ds_3^2 - dS_3^2\right)/2 &= E_{xx}dX_3^2 + 2E_{xy}dX_3dY_3 + E_{yy}dY_3^2
\end{aligned} \tag{1}$$

where dS_i and ds_i (i=1, 2, 3) are lengths of line segments of the triangle in the initial state and the deformed state, respectively, and dX_i and dY_i are x and y components of the line segments in the initial state, respectively.

Axes x and y are in horizontal and vertical directions of the image, respectively. The first image in a series of multiphase tagged images was employed as the initial state for the strain analysis. As a result, the strains calculated here are relative values based on an image at end diastole. Figures 1(a) and (b) show sample images at end diastole and end systole, respectively, in which the triangular regions for the strain analysis are constructed. Furthermore, the calculated strain tensors were translated to polar coordinates where the origin is a center of the left ventricular cavity (see Fig. 1(a)), and the radial strain E_{rr}, the shear strain $E_{r\theta}$, and the circumferential strain $E_{\theta\theta}$ in the polar coordinates system were calculated by

$$\begin{aligned} E_{rr} &= E_{xx}\cos^2\phi_{rx} + 2E_{xy}\cos\phi_{rx}\cos\phi_{ry} + E_{yy}\cos^2\phi_{ry} \\ E_{r\theta} &= E_{xx}\cos\phi_{rx}\cos\phi_{\theta x} + E_{xy}(\cos\phi_{rx}\cos\phi_{\theta y} + \cos\phi_{ry}\cos\phi_{\theta x}) + E_{yy}\cos\phi_{ry}\cos\phi_{\theta y} \\ E_{\theta\theta} &= E_{xx}\cos^2\phi_{\theta x} + 2E_{xy}\cos\phi_{\theta x}\cos\phi_{\theta y} + E_{yy}\cos^2\phi_{\theta y} \end{aligned} \tag{2}$$

where ϕ_{ij} (i=r, θ; j=x, y) is the angle between i and j axes. In order to evaluate a difference of the cardiac contractility in local regions, the left ventricular wall was divided into four regions, that is, the anterior wall, the septal wall, the posterior wall, and the lateral wall, and the calculated strains in each triangular region were averaged in each wall (see Fig. 1(b)).

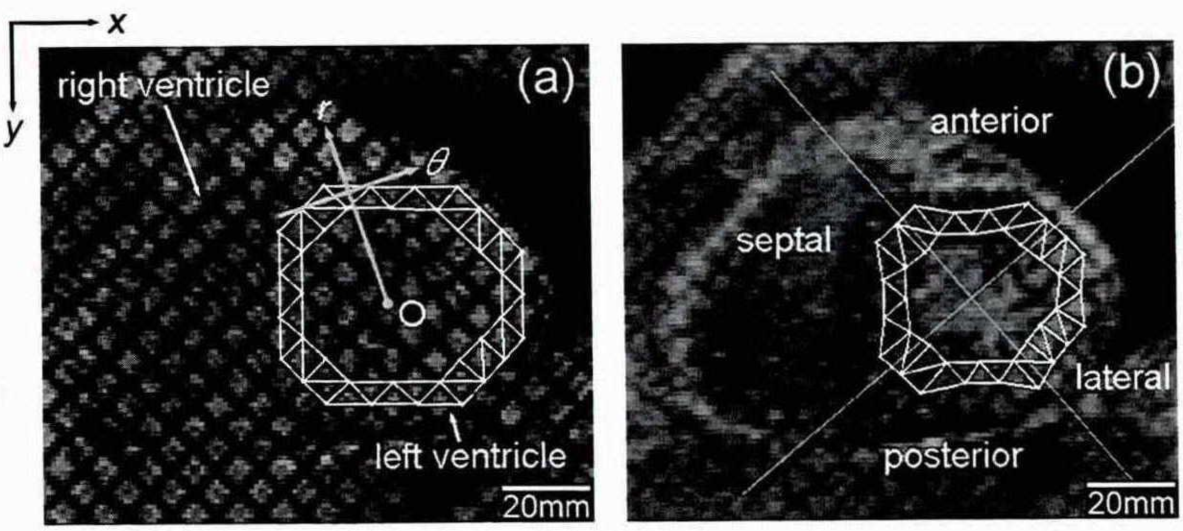

Fig. 1 Sample images with triangular regions for strain analysis
(a) End diastole, (b) End systole

4. Evaluation of Cardiac Contractility in Normal Heart

In order to clarify a difference between the cardiac contractility in normal humans and that in patients with a heart disease, to determine a quantitative reference of normal values is indispensable. In the present paper, to provide this quantitative reference, the deformations of the left ventricular walls in ten normal humans were analyzed. Figure 2 shows the magnitudes of the strain components averaged in ten normal humans at end systole. As seen in Fig. 2, the radial strains and the circumferential strains indicate positive and negative values in whole regions, respectively. It is also observed in the circumferential strains that dispersion among ten subjects is considerably small (coefficients of variations are 7.9% in the anterior wall, 12.8% in the septal wall, 10.0% in the posterior wall, and 7.2% in the lateral wall). Figure 3 shows the magnitudes of the minimum principal strains, which is one of the eigen values of the strain tensor and which represents the maximum contraction, and the circumferential strains at end systole in the normal humans. As seen in Fig. 3, the magnitude of the circumferential strain in each region is almost equivalent to the magnitude of the minimum principal strain in each corresponding region (ratios of the minimum principal strain and the circumferential strain are 96% in the anterior wall, 89% in the septal wall, 92% in the posterior wall, and 97% in the lateral wall). From these results, it is recognized that the myocardial wall dominantly contracts to the circumferential direction at a short-axis section in normal humans, and that there is no significant difference among subjects with regard to an amount of contraction of the myocardium. An index to evaluate singularity of diseases is hoped that dispersion among normal subjects is small. For this reason, the circumferential strain could be an effective index for a quantitative evaluation of heart diseases.

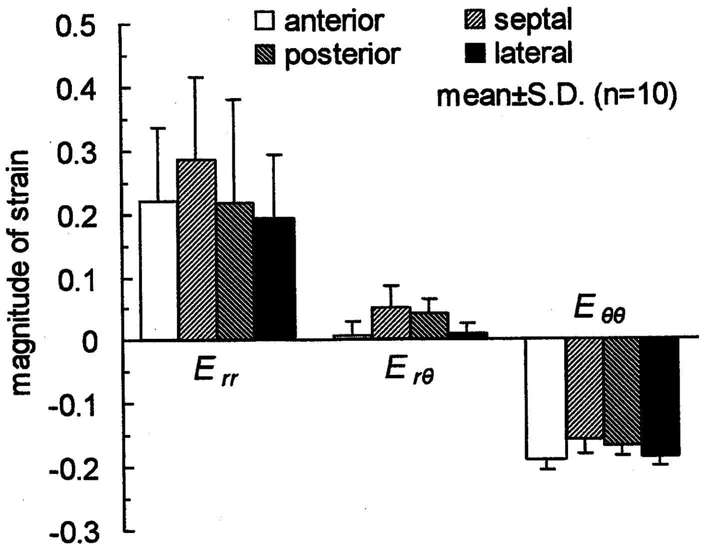

Fig. 2 Magnitudes of strain components at end systole in normal humans

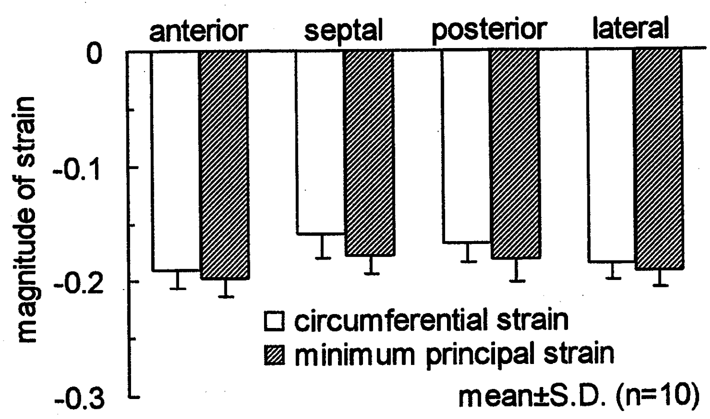

Fig. 3 Magnitudes of circumferential strains and minimum principal strains at end systole in normal humans

5. Results in Diseased Heart

The circumferential strains at end systole in the patients with a HCM are summarized in Table 1. In Table 1, an asterisk indicates an absolute value of the circumferential strain which is significantly smaller than an absolute value of mean+3.29×S.D. in corresponding region of the normal humans. As seen in Table 1, regions in which the circumferential strain is significantly small are observed in all subjects. The circumferential strains at end systole in the patients with a HHD are summarized in Table 2. As seen in Table 2, there is no region in which the circumferential strain is significantly small. Figures 4(a)-(f) show typical images of distributions of the circumferential strains at the end systole in the normal humans, the patients with the HCM, and the patients with the HHD. As seen in these figures, absolute values of the circumferential strains in local regions in the patients with the HCM, especially the septal wall in Fig. 4(c) and the anterior wall in Fig. 4(d), decreased compared with those in the normal humans, while the circumferential strains in the patients with the HHD indicate similar tendency to those in the normal humans.

Table 1 Circumferential strains at end systole in each patient with HCM

	anterior	septal	posterior	lateral
HCM A	* −0.125	* −0.085	−0.171	−0.213
HCM B	* −0.052	* −0.030	* −0.095	−0.189
HCM C	* −0.102	* −0.053	−0.151	−0.145
HCM D	−0.182	* −0.086	−0.142	−0.238
HCM E	* −0.067	−0.144	−0.184	−0.146
HCM F	* −0.141	−0.121	−0.130	−0.173
HCM G	* −0.093	* −0.059	−0.121	−0.182
HCM H	* −0.079	* −0.034	−0.136	−0.209
normal	−0.191±0.015	−0.159±0.020	−0.168±0.017	−0.186±0.013

Table 2 Circumferential strains at end systole in each patient with HHD

	anterior	septal	posterior	lateral
HHD A	−0.156	−0.152	−0.167	−0.186
HHD B	−0.173	−0.134	−0.186	−0.170
HHD C	−0.199	−0.142	−0.166	−0.188
HHD D	−0.226	−0.149	−0.154	−0.193
HHD E	−0.212	−0.155	−0.209	−0.248
HHD F	−0.190	−0.148	−0.165	−0.157
HHD G	−0.228	−0.176	−0.192	−0.221
normal	−0.191±0.015	−0.159±0.020	−0.168±0.017	−0.186±0.013

6. Discussions

As found from the obtained results, the circumferential strains in local regions of the patients with a HCM were significantly smaller compared with those in corresponding regions of the normal humans. These results suggest that HCM is a heart disease accompanied with a reduction of an amount of contraction of the myocardium, and that the circumferential strain could be an effective index for a quantitative and local evaluation of an extent of the reduction. As known in histology, disarray of the myocardium is brought about in a hypertrophic region of hearts with a HCM. It is, therefore, considered that the disarray of the myocardium causes the reduction of the cardiac contractility.

On the other hand, as found from the results in the patients with a HHD, there was no region in which the circumferential strain was significantly small, and the distributions of the circumferential strains were similar to those in the normal humans. These results suggest that an amount of contraction of the myocardium

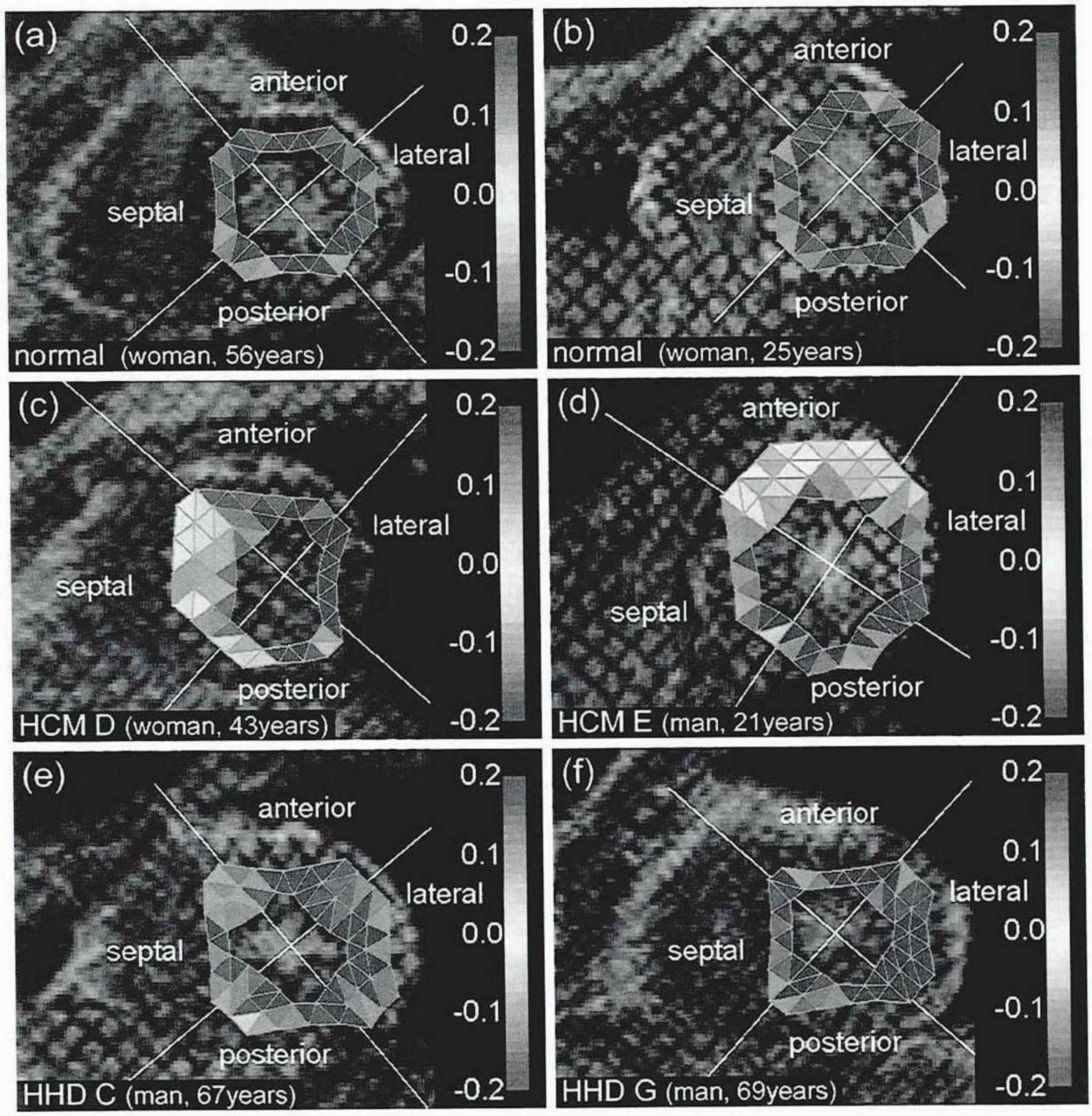

Fig. 4 Distributions of circumferential strains at end systole in left ventricular wall
(a) and (b) Normal human, (c) HCM (subject D), (d) HCM (subject E),
(e) HHD (subject C), (f) HHD (subject G)

in hearts with a HHD is almost the same as that in normal hearts. It is, therefore, considered that hypertrophy of the myocardium in this disease is not an abnormality of the myocardium, but a secondary change in order to compensate a reduction of the ejection fraction caused by hypertension.

Furthermore, as found from the above results, the cardiac contractility in HCM and that in HHD are different, although both of them are heart diseases accompanied with the hypertrophy of the myocardium. And, it is confirmed that a difference between the cardiac contractility in each heart disease is reflected in the circumferential strain.

7. Concluding Remarks

In the present paper, to investigate usefulness of a mechanical evaluation of the cardiac contractility, the deformations of the left ventricular myocardial walls during systole in the normal humans, the patients with a HCM, and the patients with a HHD were analyzed by using the magnetic resonance tagging technique. The obtained findings were summarized as follows;

(1) The circumferential strains in local regions of the patients with a HCM were significantly smaller compared with those in corresponding regions of the normal humans.

(2) The circumferential strains in whole regions of the patients with a HHD were similar to those in corresponding regions of the normal humans.

(3) The cardiac contractility in HCM and that in HHD were different, although both of them were heart diseases accompanied with the hypertrophy of the myocardium.

From these findings, it is confirmed that a characteristic of the cardiac contractility in each heart disease is reflected in the circumferential strain. This study suggests that to evaluate the cardiac contractility from a mechanical point of view by analyzing the deformation of the myocardial wall is useful for a quantitative evaluation of heart diseases.

Acknowledgments

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