Two-Dimensional Deformation Analysis of Human Left Ventricle during Ejection Period Using Magnetic Resonance Tagging Technique*

Tadashi INABA**, Masataka TOKUDA**, Yasutomi KINOSADA***,
Yutaka SAWAKI** and Kazuo YAGI**

The two-dimensional deformations of human left ventricles (Subjects were four normal volunteers and a patient with a hypertrophic cardiomyopathy) during the ejection period were investigated using the magnetic resonance tagging technique. The displacements were measured by tracking the intersections of tagged stripes formed within the left ventricular myocardial wall, and the strains were calculated from the changes of segment lengths of triangles defined by three adjoining intersections. It was recognized from the results for the normal volunteers that the magnitudes of minimum principal strains were almost uniform over all regions (anterior, septal, posterior and lateral) of the left ventricular wall, while the magnitudes of displacements were different from regions to regions. The magnitude of minimum principal strain in the anterior wall of the heart with the disease was smaller compared with those of the normal hearts. This study may suggest that the minimum principal strain could be an alternative effective index to evaluate the cardiac contractility.

Key Words: Biomechanics, MR Tagging Technique, Human Left Ventricle, Ejection Period, Principal Strain, Cardiac Contractility

1. Introduction

The heart, especially the left ventricle, plays a role as the ejection pump in the blood circulation system. The ejection of the blood is caused by the contraction of myocardial fiber. Therefore, it is important to analyze the contractile mechanism of myocardium from a mechanical point of view, in order to evaluate the cardiac function. To obtain the precise motion of myocardial wall motion, attaching some landmarks to the wall and tracking them throughout a cardiac cycle are required. In a decade, the measurement and analysis of myocardial wall motion have been studied by the methods using the implanted markers as the landmarks^{(1), (2)}. However, these techniques cannot be applied to practice in

medical facilities by the invasiveness of implantation.

On the other hand, the remarkable progresses of medical imaging techniques such as echocardiography, X-ray computed tomography and magnetic resonance imaging (MRI) have made it possible to obtain the noninvasive information in the living body. Among others, MRI is attracted in recent years, because this imaging technique makes it possible to obtain the images containing the various information by inventing the combination of imaging parameters called the pulse sequence. The MR tagging technique⁽³⁾⁻⁽⁵⁾ is one of these invented pulse sequences. By applying this technique, the patterns of stripes can be formed in an imaging object by modifying spatially the states of nuclear spins at the specific positions. The tagged stripes move together with the motion of imaging object. Therefore, the noninvasive measurement and analysis of human myocardial wall motion have become possible^{(6), (7)} by imaging the heart using the MR tagging technique and tracking the movements of stripes within the myocardial wall.

From the above-mentioned point of view, the two-dimensional deformations of left ventricles were investigated using the MR tagging technique for four

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** Department of Mechanical Engineering, Mie University, 1515 Kamihama, Tsu 514, Japan

*** Department of Radiology, Kyoto Prefectural University of Medicine, Kawaramachi Hirokoji, Kamigyo, Kyoto 602, Japan

normal volunteers and a patient with a hypertrophic cardiomyopathy, in this research work. The displacements were measured by tracking the intersections of tagged stripes formed within the myocardial wall, and the strains were calculated from the changes of segment lengths of triangles defined by three adjoining intersections. By using these deformation parameters, we discussed that what kind of physical quantity is effective as an index to evaluate the cardiac contractility. Such index could be useful in order to evaluate quantitatively the extent of heart disease or the effect of treatment.

2. Image Acquisition

Four normal volunteers (men aged 21 to 24 years) and a patient with a hypertrophic cardiomyopathy (man aged 44 years) were imaged with a 1.5 T superconducting magnet (SIGNA ADVANTAGE, GE). The imaging procedure to obtain the short axis images of left ventricle is as follows;

(1) Coronal spin-echo images are obtained to identify the cardiac position.

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

(3) A long axis of left ventricle is determined to pass through a point at the center of aortic root and a point at the apex, as seen in the oblique image.

(4) Multiphase tagged short axis images at the equatorial plane of left ventricle are obtained perpendicular to the determined long axis.

The first tagged image was obtained after 70 ms from the detection of the R wave of the electrocardiogram, and the subsequent tagged images were obtained continuously at 50 ms intervals. It was assumed that the first image corresponds to that at the end of isovolumic contraction and the 5th or 6th image

Fig. 1 A sample image acquired MR tagging technique at end of isovolumic contraction

corresponds to that at the end of ejection period (depending on the heart rate of each subject). Figure 1 shows a sample image acquired by the MR tagging technique at the end of isovolumic contraction for a normal volunteer. In the images acquired in this research work, a field of view, an image matrix, a slice thickness and a space of tagged stripes are $320 \times 320 \text{ mm}^2$, 256×256 pixels, 10 mm and 7 mm, respectively.

3. Deformation Analysis

3.1 Measurement of displacement

The stripes, which were tagged in an imaging object by the MR tagging technique, formed a number of intersections within the myocardial wall, as shown in Fig. 1. The displacements were measured by tracking the intersections of tagged stripes through the ejection period. The image at the end of isovolumic contraction (the first image) was used as the reference for the measurement of displacement. The magnitudes of displacements were defined as the distances between the intersections in the first image and the corresponding intersections in the subsequent images.

3.2 Calculation of strain

The intersections of tagged stripes were also utilized for the calculation of strain. The components of strain tensor, E_{xx} , E_{xy} and E_{yy} within a triangular region defined by three adjoining intersections were calculated by

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

where dS_i and ds_i ($i=1, 2, 3$) are the segment lengths of triangle in the first image and the subsequent images, respectively, and dX_i and dY_i are x and y components of segment lengths in the first image. Axes x and y are in the horizontal and vertical directions of image, respectively. The magnitude and the direction of minimum principal strain were calculated by the following equation

$$\begin{aligned} E_2 &= \frac{1}{2}(E_{xx} + E_{yy}) - \frac{1}{2}\sqrt{(E_{xx} - E_{yy})^2 + 4E_{xy}^2} \\ \theta &= \frac{1}{2} \arctan \frac{2E_{xy}}{E_{xx} - E_{yy}} + \frac{\pi}{2} \end{aligned} \quad (2)$$

The magnitude of minimum principal strain E_2 , one of eigenvalues of strain tensor, describes the maximum contraction of triangular region, and the direction of minimum principal strain θ describes the orientation in which the minimum principal strain acts. The strains calculated here are the relative values from the end of isovolumic contraction, thus, these are not the absolute values inducing practically in the left

ventricular myocardial wall. Figure 2 shows a sample image with the triangular regions for the calculation of strain.

4. Classification of Local Region of Left Ventricle

In order to investigate the difference of deformation in the local regions, the left ventricle in the short axis image was divided into four regions (anterior, septal, posterior and lateral) for convenience. The procedure is as follows (see Fig. 3);

(1) The centers of left and right ventricle are determined using the image at the end of ejection period.

(2) Cross section mm is defined as a line connected two centers, and cross section nn is defined as a line perpendicular to mm through the center of left

Fig. 2 A sample image with triangular regions for calculation of strain

ventricle.

(3) By using the angle ϕ measured from mm , the left ventricle is divided equally into four regions, that is, the anterior wall ($\pi/4 < \phi \leq 3\pi/4$), the septal wall ($3\pi/4 < \phi \leq 5\pi/4$), the posterior wall ($5\pi/4 < \phi \leq 7\pi/4$) and the lateral wall ($7\pi/4 < \phi \leq \pi/4$).

5. Results and Discussions

5.1 Displacement for normal volunteers

Figure 4 shows the images with the displacement vectors for the four normal volunteers. The images are at the end isovolumic contraction, which are used as the reference for the measurement, and the arrows in these images indicate the displacement vectors at the end of ejection period. Figure 5 shows the time variations of magnitudes of displacements averaged in each region during the ejection period. The horizontal axes indicate the time passing from the end of isovolumic contraction to the end of ejection period,

Fig. 3 Schematic representation of divided regions

Fig. 4 Images with displacement vectors for normal volunteers

which depends on the heart rate of each subject (200 ms for subject A, B and D, 250 ms for subject C). As seen in Fig. 4, the magnitudes of displacements are different from regions to regions, although the directions of displacements are toward the center of left ventricular cavity. From Fig. 5, the maximum values of averaged displacement are approximately 2 times as large as the minimum values at the end of ejection period for all subjects (5.9 versus 2.9, 6.4 versus 2.6, 7.6 versus 4.0 and 6.6 versus 2.6 mm, for subject A, B, C and D, respectively). The magnitude of displacement in the anterior wall is minimum for subject D, while the magnitudes of displacements in the septal wall are minimum for the other subjects. This difference is understood by considering the position of each heart in the body, that is, the hearts of subject A, B and C are in contact with the thoracic wall at the right ventricle, while the heart of subject D is in contact with the thoracic wall at the anterior wall of left ventricle. It is considered that the magnitude of

displacement in the local region of left ventricle depends on the state of restriction of each heart in the body.

5.2 Strain for normal volunteers

In this paper, in order to evaluate the contractility of the left ventricular myocardial wall during the ejection period, we discuss about the minimum principal strain corresponding to the maximum contraction.

Figure 6 shows the time variations of magnitudes of minimum principal strains averaged in each region during the ejection period. The averaged values of minimum principal strains in each region at the end of ejection period, and their mean values and standard deviations are summarized in Table 1. As seen in Fig. 6 and Table 1, the magnitudes of minimum principal strains are almost uniform over all regions for all subjects, and there is no significant difference among four subjects. These results represent that the contraction of myocardial wall is uniform over all regions for the normal volunteers. Figure 7 shows the images

Fig. 5 Time variations of magnitudes of displacements during ejection period for normal volunteers

Fig. 6 Time variations of magnitudes of minimum principal strains during ejection period for normal volunteers

Table 1 Averaged values of minimum principal strains in each region at end of ejection period

	Anterior	Septal	Posterior	Lateral	Mean $\pm$ SD
Subject A	-0.144	-0.163	-0.164	-0.156	-0.157 ± 0.010
Subject B	-0.150	-0.156	-0.182	-0.155	-0.161 ± 0.015
Subject C	-0.148	-0.140	-0.143	-0.170	-0.150 ± 0.014
Subject D	-0.158	-0.182	-0.161	-0.171	-0.168 ± 0.011
Mean $\pm$ SD	-0.150 ± 0.006	-0.160 ± 0.017	-0.163 ± 0.016	-0.163 ± 0.009	-0.159 ± 0.013

Fig. 7 Images with triangular regions for calculation of strain for normal volunteers

with the triangular regions for the calculation of strain for the four normal volunteers. The line segments within the triangular regions indicate the magnitudes and directions of minimum principal strains at the end of ejection period. The circumferential direction is dominant for the directions of minimum principal strains as seen in this figure. It is suggested that the direction of minimum principal strain closely relates to the myocardial fiber orientation, because the project direction of myocardial fiber orientation on the short axis plane is circumference⁽⁸⁾.

In the above-mentioned results for the normal volunteer, the magnitudes of minimum principal strains are almost uniform over all local regions and there is no significant difference among each subject, while the magnitudes of displacements are different from regions to regions. This constancy of minimum principal strain in the normal hearts may suggest the effectivity of this physical quantity as an index to evaluate the cardiac contractility.

5.3 Deformation for a patient with a disease

Figure 8(a) shows the image with the displace-

ment vectors at the end of ejection period, and Fig. 8(b) shows the time variations of magnitudes of displacements during the ejection period for a patient with a hypertrophic cardiomyopathy. Figure 9(a) shows the image with the line segments corresponding to the minimum principal strains at the end of ejection period, and Fig. 9(b) shows the time variations of magnitudes of minimum principal strains during the ejection period for the patient. In Fig. 8(b), the magnitude of displacement at the end of ejection period in the septal wall is minimum, and this heart is in contact with the thoracic wall at the right ventricle as seen in Fig. 8(a). These results show the similar tendency to the case of normal volunteers (subject A, B and C). However, as seen in Fig. 9(a) and (b), the magnitude of minimum principal strain at the end of ejection period in the anterior wall of this heart is seriously smaller compared with those of all normal hearts (0.04 versus 0.144, 0.150, 0.148 or 0.158). It is recognized from the results that the reduction of contraction of myocardium occurs in the anterior wall of this heart. Therefore, it is considered that the

(a) An image with displacement vectors

(b) Time variations of magnitudes of displacements during ejection period

Fig. 8 Displacements for a patient with a hypertrophic cardiomyopathy

minimum principal strain has the ability of detection of singular region in the heart with the disease.

6. Concluding Remarks

In this research work, the two-dimensional deformations in the human left ventricular myocardial wall during the ejection period were investigated using the MR tagging technique, in order to provide an index to evaluate the cardiac contractility. The following findings were obtained.

(1) The magnitudes of minimum principal strains are almost uniform over all regions for the normal volunteers, while the magnitudes of displacements are different from regions to regions.

(2) The magnitude of minimum principal strain in anterior wall of the heart with the disease is smaller compared with those of the normal hearts.

From these findings, it is suggested that the minimum principal strain could be an alternative effective index to evaluate the cardiac contractility. However, in order to confirm the effectiveness of this index, it is required that a number of myocardial motions are investigated by applying this technique to patients with several types of diseases.

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(a) An image with triangular regions for calculation of strain

(b) Time variations of magnitudes of minimum principal strains during ejection period

Fig. 9 Minimum principal strains for a patient with a hypertrophic cardiomyopathy

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