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Quantitative Evaluation of Left Ventricular Wall Motion in Patient with Coronary Artery Bypass Grafting Using Magnetic Resonance Tagging Technique*

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Left ventricular wall motions during systole were investigated from a mechanical perspective by using a magnetic resonance tagging technique. Subjects were 7 patients with coronary artery bypass grafting (CABG). First, by analyzing strain in the left ventricular wall, cardiac contractility was evaluated in the patients with CABG. Next, by calculating displacement in the myocardial wall, paradoxical movements following CABG were quantitatively evaluated. Strain analysis showed local decreases in circumferential strain in 4 of 7 subjects. The results of displacement analysis clarified that following CABG, the degree of radial displacement was small in the septal wall and large in the lateral wall, and circumferential displacement towards the septal wall occurred in the anterior and posterior walls. Since this behavior was seen in both reduced and normal cardiac contractility groups, paradoxical movements in the present patients were not caused by reduced cardiac contractility, but rather by rigid-body motion of the entire heart.

Key Words: Biomechanics, Magnetic Resonance Tagging Technique, Left Ventricular Wall Motion, Coronary Artery Bypass Grafting, Cardiac Contractility, Rigid-Body Motion

1. Introduction

Analyzing deformation behaviors of the myocardial wall and evaluating cardiac contractility from the perspective of mechanics are useful in gathering information for quantifying and diagnosing the severity of heart diseases and evaluating therapeutic effects. This requires noninvasive evaluation of myocardial wall motions, and magnetic resonance (MR) tagging(1)-(3) is one such evaluation technique. In MR tagging, before a conventional pulse sequence is delivered, the nuclear spin of protons at a specific position within a target region is spatially altered to add stripe or lattice patterns. Such tagged patterns move and change with movements of the target region. Using this technique, myocardial wall motions can be noninvasively evaluated by continuously scanning cross-sections of the heart during different cardiac phases(4)-(12).

The energy demands of biological tissue are maintained by blood circulation via the pumping action of the heart, and the heart itself receives blood via the coronary circulation system. When coronary circulation is hindered, normal myocardial metabolism is disrupted and cardiac function is compromised. Heart diseases caused by reduced coronary flow or insufficiency are called ischemic heart diseases(13), and coronary artery bypass grafting (CABG) is one of the treatment options. CABG is an operation where another vessel is anastomosed to bypass a stenosed or occluded coronary artery to increase blood flow beyond the affected area. Unlike percutaneous transluminal coronary angioplasty (PTCA), CABG requires thoracotomy and pericardiotomy, and thus has been known to cause such paradoxical movements as sep-

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tal wall movement towards the right ventricle. However, few studies have quantitatively evaluated myocardial wall motions from a mechanical perspective.

In the present study, MR tagging, a noninvasive imaging technique to evaluate myocardial wall motions, was used to mechanically and quantitatively evaluate myocardial wall motions. By analyzing left ventricular myocardial wall strain during systole, cardiac contractility was evaluated in patients with CABG. In addition, by calculating displacement in the myocardial wall, paradoxical movements following CABG were quantitatively evaluated, and factors contributing to such movements were discussed.

2. Subjects and Methods

2.1 Patients and imaging methods

MR tagging was performed on 7 patients who had undergone CABG. Patient information is summarized in Table 1. In all subjects, heart rate was stable during imaging and no arrhythmias were encountered. A 1.5-T scanner (Signa Advantage; GE Medical Systems) was used for all MRI.

To obtain short-axis cross-sections of the left ventricle, conventional gradient-echo MRI was first performed to capture coronal sections and identify location of the heart, then cross-sections were captured along the line connecting the aortic root and the left ventricular apex. The long axis of the left ventricle was defined as the line passing through the center of the mitral valve ring and the left ventricular apex. After determining the long-axis, multiphasic electrocardiography (ECG)-gated short-axis cross-sections in the equatorial plane of the left ventricle perpendicular to the long axis were continuously captured. As the pulse sequence in imaging, the SPAMM procedure(2),(3) was used to tag periodic lattice stripes, and high-speed scanning was employed for motion image collection to obtain echo signals by rotating the magnetic gradient. Imaging conditions were as follows: scanning area, $280\times280\,\mathrm{mm}^2$; image matrix, 256×256 pixels; slice thickness, 10 mm; tag interval, 7 mm; and repeat time, 25 ms. In the present study, tagged motion images were continuously captured at a 25-ms interval, with the first image captured 20 ms after detection of the R wave by ECG gating. The first image in the tagged motion image series thus represented end diastole, while an image with the smallest left ventricular cavity represented end systole. Figure 1 shows sample images obtained by MR tagging technique. Black lattice patterns on the images represented tagging.

Table 1 Summary of patient information

subject	primary disease	age [yrs]	sexuality
A	AP	48	male
B	AP	76	female
C	AP	54	male
D	AP	66	male
E	MI	50	male
F	MI	70	male
G	MI	66	female

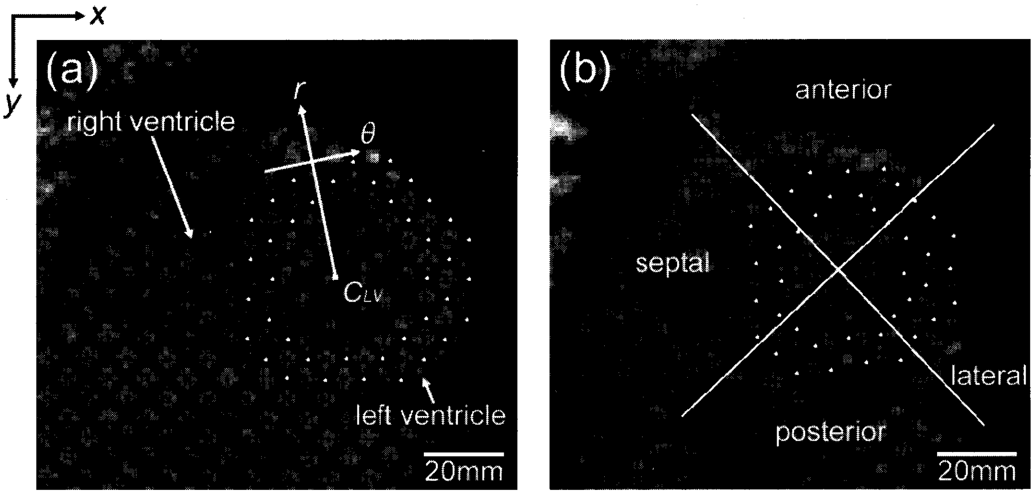
AP:angina pectoris, MI:myocardial infarction

2.2 Analysis methods

Lattice tagging of a target region using the above-mentioned tagging technique was visualized as numerous intersections inside the myocardial wall. While the tag was seen in the motion image series, these intersections functioned as material points. In the present study, intersections were visually followed during systole to calculate left ventricular myocardial wall displacement and strain.

First, displacement vector components u_x and u_y were calculated using the following formulae:

$$\begin{aligned} u_x &= x - X \\ u_y &= y - Y \end{aligned} \tag{1}$$



(a) End diastole (b) End systole

Fig. 1 Sample images obtained by MR tagging technique where X and Y are the x and y coordinates of a tag intersection before deformation, respectively, and x and y are the x and y coordinates of the tag intersection after deformation, respectively. The x and y axes also represent the horizontal and vertical directions of images, respectively (Fig. 1). The end diastolic image was used as the base image for displacement calculations (pre-deformation state). In the end diastolic image, blood inside the left ventricle was also tagged (Fig. 1 (a)). The end systolic image (Fig. 1 (b)) was thus used to select intersections for displacement calculation. In the end systolic image, tagged blood in the end diastolic image had already pumped away from the cross section, and the ventricular cavity and myocardial wall were readily differentiated.

Next, strain tensor components E_{xx}, E_{yy} and E_{xy} were calculated using the formulae below. For this analysis, the left ventricle comprised triangular regions made of 3 adjacent tag intersections.

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

where dS_i and ds_i $(i = 1,2,3)$ are the lengths of each side of the triangle before and after deformation, respectively, and dX_i and dY_i $(i = 1,2,3)$ are the x- and y-axis components of each side of the triangle before deformation, respectively.

The coordinate system used for calculating the above-mentioned displacement and strain correlated to captured images and was not based on anatomical positional information of the heart. Calculated displacement and strain components were therefore subjected to conversion to a Cartesian coordinate system with an r axis [radial (wall thickness) direction], a θ axis (circumferential direction) and origin (center of the left ventricular cavity) (Fig. 1 (a)). In this coordinate system, u_r (radial displacement component), u_θ (circumferential displacement component), E_{rr} (radial strain component), $E_{r\theta}$ (shear strain component) and $E_{\theta\theta}$ (circumferential strain component) were calculated. Also, to locally evaluate myocardial contractility, calculated displacement and strain components were averaged for the following 4 areas: anterior wall; septal wall; posterior wall; and lateral wall (Fig. 1 (b)).

3. Strain Analysis

3.1 Results

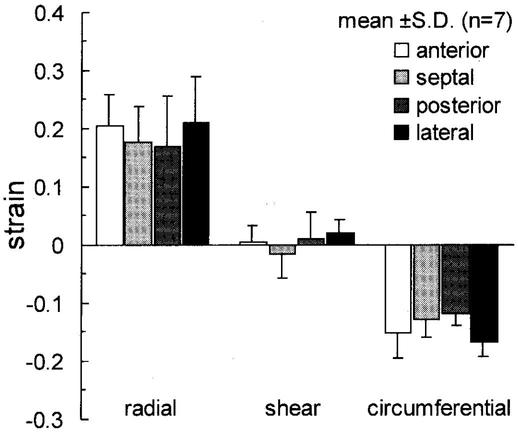


Fig. 2 Mean of strain component at end systole in patients with CABG

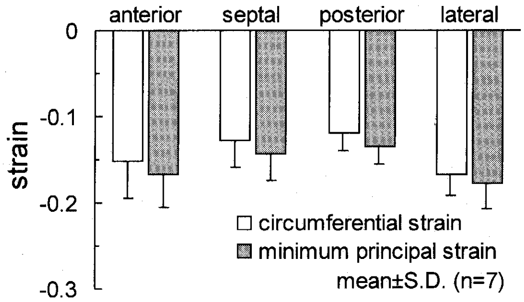


Fig. 3 Comparison between circumferential strain and minimum principal strain at end systole

Figure 2 shows the mean of strain component at end systole in patients with CABG, and Fig. 3 compares circumferential strain and minimum principal strain (maximum contraction in a region of interest, and one of the eigen values of strain tensor). In all 4 areas (anterior wall, septal wall, posterior wall and lateral wall), radial strain displayed positive values, shear strain was almost zero, and circumferential strain had negative values (Fig. 2). Furthermore, circumferential strain was comparable to minimum principal strain in each area (ratio of circumferential strain to minimum principal strain was 91% for anterior wall, 89% for septal wall, 89% for posterior wall, and 94% for lateral wall) (Fig. 3).

Table 2 shows the circumferential strain at end systole in each patient with CABG, and the mean and standard deviation of circumferential strain for 10 healthy individuals (6 men, 4 women; age range, 21–56 years) in another study(11). Asterisks indicate that the absolute value of strain for the subject was below the normal range for healthy individuals (mean ±2.58 standard deviations, or 99% confidence interval for the normal distribution of strain for healthy individuals). Furthermore, ratio of strain for each subject was determined in relation to mean strain of the healthy individuals. In 4 of the 7 subjects, circumferential strain was decreased in some areas. The ratio was the lowest for the anterior wall of Subject A, at about 50%. Positive values of circumferential strain (i.e., extension in the circumferential direction) were not identified in any subject.

3.2 Discussion

Strain analysis shows that, following CABG, the myocardium stretches in the radial direction during systole and predominantly contracts in the circumferential direction. As reported previously(11), in healthy individuals on short-axis cross sections, the myocardium stretches in the

Table 2 Circumferential strain at end systole in each patient with CABG

subject	anterior	septal	posterior	lateral
A	* -0.094 (49%)	* -0.097 (61%)	* -0.099 (59%)	-0.180 (97%)
B	-0.158 (83%)	-0.170 (107%)	-0.132 (79%)	-0.165 (89%)
C	-0.223 (117%)	-0.157 (99%)	-0.149 (88%)	-0.196 (105%)
D	-0.155 (81%)	* -0.096 (61%)	* -0.118 (70%)	-0.152 (82%)
E	* -0.122 (64%)	-0.110 (69%)	* -0.108 (64%)	* -0.123 (66%)
F	-0.184 (96%)	-0.152 (96%)	-0.135 (81%)	-0.188 (101%)
G	* -0.125 (65%)	-0.109 (69%)	* -0.096 (57%)	-0.164 (88%)
healthy human (mean±S.D.)	-0.191±0.015	-0.159±0.020	-0.168±0.017	-0.186±0.013

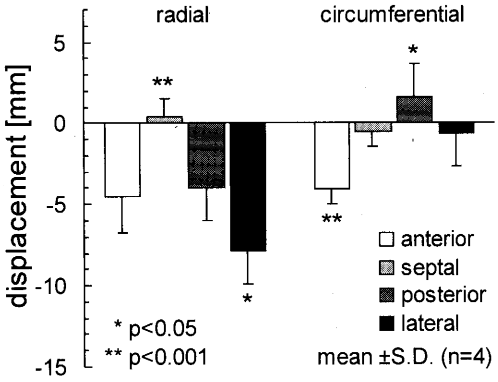
radial direction and predominantly contracts in the circumferential direction. In the present subjects, strain behaviors were qualitatively the same. However, from the viewpoint of quantitative data, about 60% of the subjects displayed reduction in circumferential strain over a broad area around the posterior wall. Therefore, even if coronary blood flow recovers following bypass surgery, not all patients can maintain a level of cardiac contractility comparable to healthy individuals. However, in areas with reduced cardiac contractility, myocardium did not stretch circumferentially, and strain was > 50% of that in healthy individuals. Villarreal et al.(14) investigated myocardial wall strain in ischemic canine hearts and reported that myocardium contracted circumferentially without ischemia, but stretched in 5–10 min after ischemia. Based on these results, in all subjects in the present study, increased blood flow due to CABG allowed some myocardial cells to survive. Based solely on the results of postoperative analysis, whether surviving myocardial cells existed before surgery or were revived after CABG could not be clarified. Since this point is extremely important for evaluation of the therapeutic effects of CABG, further investigations are warranted.

4. Displacement Analysis

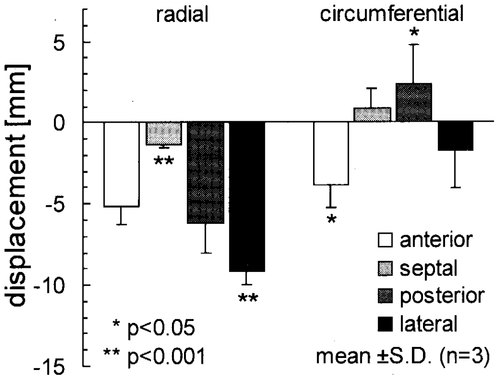
4.1 Results

Based on the results of strain analysis, the 7 subjects were divided into the following 2 groups: reduced cardiac contractility (Subjects A, D, E and G); and normal cardiac contractility (Subjects B, C and F), and myocardial wall motions were quantified following CABG.

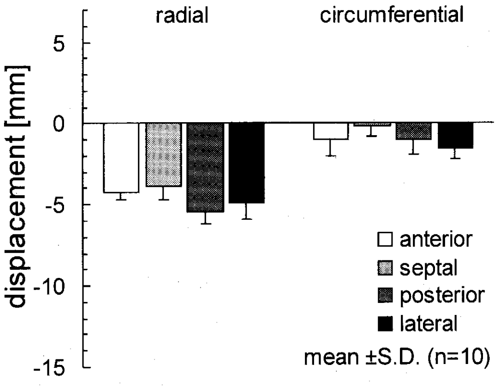
Figure 4 (a)–(c) shows the mean of displacement component at end systole for reduced cardiac contractility, normal cardiac contractility and healthy groups, respectively. In addition, Fig. 5 (a) and (b) shows sample images with displacement vector at end systole in a patient with CABG and a healthy individual, respectively. In healthy individuals, the myocardial wall was displaced towards the cavity center with minimum circumferential displacement, and degree of displacement was 3.9–5.4 mm (Fig. 5). After CABG, degree of radial displacement was



(a) Reduced cardiac contractility group

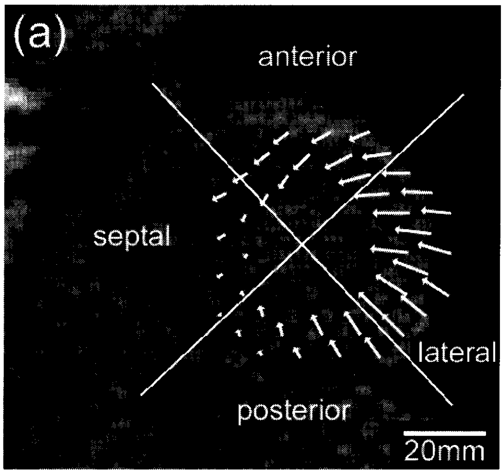


(b) Normal cardiac contractility group

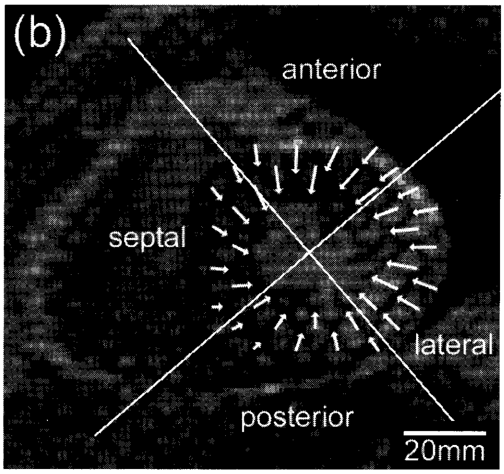


(c) Healthy group

Fig. 4 Mean of displacement component at end systole



(a) Patient with CABG (subject G)



(b) Healthy individual (56 yrs, female)

Fig. 5 Sample images with displacement vector at end systole. In the figures, the arrows show the displacement vector for each calculation point.

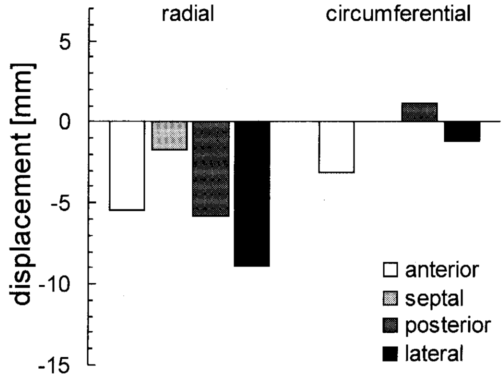


Fig. 6 Displacement component at end systole in a patient with ASD closure

almost zero for the reduced group and 1.3 mm for the normal group. A 2-sample t-test showed that radial displacement was significantly smaller for the reduced and normal groups when compared to the healthy group. In addition, degree of radial displacement of the lateral wall was 7.8 mm for the reduced group and 9.1 mm for the normal group, significantly greater than in the healthy group. Furthermore, compared to the healthy group, differences in circumferential displacement of the anterior and posterior walls were noted, and displacement towards the septal wall was seen in these areas.

Figure 6 shows the displacement component at end systole in a 57-year-old man who underwent surgery for the treatment of atrial septal defect (ASD). Myocardial wall motions following ASD closure surgery were similar to those following CABG (Fig. 6). In other words, degree of radial displacement was small in the septal wall and large in the lateral wall, and in the anterior and posterior walls, circumferential displacement occurred towards the septal wall.

4.2 Discussion

In general, displacement is a mechanical quantity that involves rigid-body motion (translation and rotation) and pure deformation (extension/contraction and distortion) of an object. Hence, displacement of each material point of an object is markedly dependent on not only material deformation, but also rigid-body motion.

The results of displacement analysis clarified that, following CABG, degree of radial displacement was small in the septal wall and large in the lateral wall, and circumferential displacement towards the septal wall was seen for the anterior and posterior walls. This behavior was also seen for both reduced and normal cardiac contractility groups. This suggests that paradoxical movements following CABG are not caused by reduced cardiac contractility, but rather by rigid-body motion of the entire heart. Figure 7 shows a schematic diagram of left ventricular wall motion in patients with CABG that was prepared based on the results of displacement and strain analyses in the present study. Following CABG, a rigid-body motion where the left ventricular side moves horizontally to the right ventricular side is believed to occur (Fig. 7).

Analysis of a patient who underwent ASD closure surgery confirmed comparable behaviors. In operations that require thoracotomy, such as CABG and ASD closure, the pericardium (parietal plate) is opened to expose the inner structures of the heart for various therapeutic procedures. To prevent pericardial fluid retention, the incised pericardium is left open following surgery. The above-mentioned rigid-body motion following CABG or ASD thus involve changes in restraining conditions of the heart in the body due to pericardiotomy.

From the perspective of evaluating cardiac contractility, analysis of myocardial wall strain is important, particularly circumferential strain on short-axis cross-sections, but analyzing displacement is not as important. However, if changes in rigid-body motion of the entire heart somehow affect the environment surrounding the heart, quan-

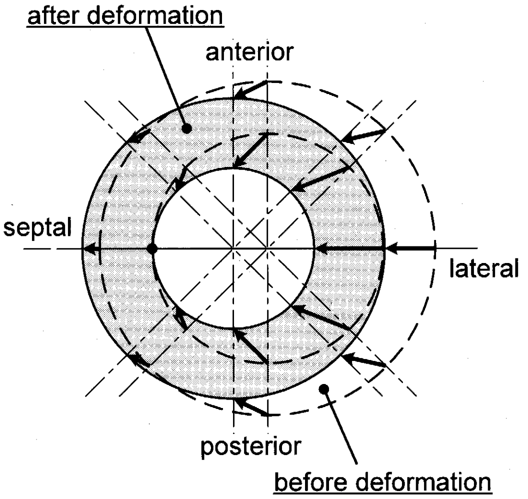


Fig. 7 Schematic diagram of left ventricular wall motion in patients with CABG. In the figure, objects depicted using broken and solid lines indicate the left ventricular wall before deformation (end diastole) and after deformation (end systole), respectively, and the arrows indicate displacement vectors.

tification of myocardial wall motions due to displacement is important. In future, we plan to investigate the prognosis of subjects in the present study.

5. Conclusions

In the present study, MR tagging was used to quantify myocardial wall motions following CABG from a mechanical perspective. By analyzing left ventricular wall strain and displacement during systole, cardiac contractility following CABG was investigated, and paradoxical movements were quantified. The results clarified the following:

(1) Strain analysis showed local decreases in circumferential strain in 4 of 7 subjects. However, even in an area where decrease in strain was strongest, degree of decrease was about 50% of that in healthy individuals, suggesting that myocardium survives to some degree.

(2) The results of displacement analysis clarified that following CABG, the degree of radial displacement was small in the septal wall and large in the lateral wall, and circumferential displacement towards the septal wall occurred in the anterior and posterior walls. Since this behavior was seen in both reduced and normal cardiac contractility groups, paradoxical movements in the present patients were not caused by reduced cardiac contractility, but rather by rigid-body motion of the entire heart.

To further clarify cardiac function, estimation of various mechanical factors that cannot easily be measured is required, such as stress distribution in the myocardial wall. When investigating the effects of heart structures (fiber alignment and stimulus transmission pathway) on cardiac function, ascertaining deviations in cardiac structures is useful. In such analysis, cardiac function assessment by numerical simulation(15),(16) is extremely useful, and deformation analysis of actual hearts is also important in verification of the results of numerical analyses.

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