Regional wall motion and strain of transplanted hearts in pediatric patients using magnetic resonance tagging

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1Division of Cardiology, Department of Pediatrics, 2Department of Surgery, and 3Department of Radiology, The University of Pennsylvania Hospital, Philadelphia, Pennsylvania 19104; and 4Division of Cardiology, Department of Pediatrics, The Medical College of Virginia of the Virginia Commonwealth University, Richmond, Virginia 23298

Donofrio, Mary T., Bernard J. Clark, Claudio Ramaciotti, Marshall L. Jacobs, Kenneth E. Fellows, Paul M. Weinberg, and Mark A. Fogel. Regional wall motion and strain of transplanted hearts in pediatric patients using magnetic resonance tagging. Am. J. Physiol. 277 (Regulatory Integrative Comp. Physiol. 46): R1481–R1487, 1999.—Abnormal ventricular systolic torsion is present during histological rejection in adult cardiac transplant patients. Because biomechanical properties of transplanted hearts in the baseline state have not been studied in children, pediatric patients were evaluated to quantify ventricular wall motion and strain. Eight transplant studies and eight normal controls were evaluated. Magnetic resonance tagging was performed to determine radial shortening, twist, and strain in four ventricular anatomic areas at two short-axis levels. Controls had counterclockwise twist. Six transplant studies had clockwise twist, six had akinetic regions, and all had regions of no twist. One demonstrated paradoxical motion of the septum. A comparison between transplant patients and controls revealed strain to be similar in all regions except one (superior wall at the atrioventricular valve level) and strain distribution to be different only in two of eight regions. Pediatric transplant patients demonstrate regional wall motion abnormalities in the absence of rejection. Compared with normal controls, the transplanted left ventricle maintains normal strain in the presence of abnormal twist. This may be a compensatory mechanism and have clinical implications.

WHEN VIEWED FROM APEX TO base, the short axis of the normal left ventricle contracts in a counterclockwise fashion during systole (5, 10, 16). Hansen et al. (10) found, after implanting intramyocardial markers in transplanted hearts, that torsional deformation was sensitive to the contractile state of the myocardium, and a decrease in the amplitude and rate of this torsional deformation was seen in patients suffering from acute rejection confirmed by biopsy (11). Because magnetic resonance imaging (MRI), using spatial modulation of magnetization (SPAMM) (1, 2, 15, 16), has the ability to tag the myocardium noninvasively, alterations in regional wall motion, represented as twist and radial shortening, may be detected similarly to the alterations in torsion detected by the implanted myocardial markers. Strain, another biomechanical parameter that can be determined by MRI, is a unitless measurement of deformation that partially characterizes the contractile state of the myocardium. With knowledge of the noninvasive nature of MRI, it may be beneficial to follow transplant patients with this technique to detect ventricular dysfunction and cellular rejection and potentially decrease the need for endomyocardial biopsy.

With the work of Hansen and colleagues in mind, an understanding of the biomechanics of the transplanted heart in the absence of rejection is key to determining the changes that occur during rejection. The biomechanical properties of the transplanted ventricle may not be the same as a normal ventricle that is innervated, has not undergone circulatory arrest, is not subjected to the toxic effects of immunosuppressant drugs, and is not at risk for rejection. We hypothesize that wall motion and strain in this patient population are different from the normal left ventricle for just these reasons. Because studies in the pediatric transplant population are lacking such biomechanical data, we undertook this study to quantify baseline properties of regional wall motion and strain in these patients.

It is important to note that this "pilot" study, because of its relatively small number of patients and comparison with young adult left ventricles, is only the first step in a long line of investigation. It must be viewed as "hypothesis generating."

METHODS

Patient Population

Twelve patients under 12 years of age who had undergone an orthotopic heart transplant at The Children's Hospital of Philadelphia were studied with MRI between August, 1993 and September, 1994. One patient had two studies, ~1 yr apart. Five patients were excluded due to the following: inadequate electrocardiographic gating (n = 2), inadequate sedation (n = 1), and/or malfunction of the imaging system (n = 2). MRI with SPAMM has been approved by the review board at our institution, and informed consent was obtained from the families of all patients. Imaging was done within 19 ± 1.9 days (range 1–6 days) prior to endomyocardial biopsy in six of the eight studies used for analysis. One patient did not have a biopsy at the time of catheterization, and the other underwent catheterization and biopsy 3.7 mo prior to imaging. The patient age was 5.1 ± 3.7 yr (range 18 daylight-11.2 yr), which was 2.6 ± 1.2 yr (range 6 mo-4 yr) posttransplant. All patients were clinically well.

Eight volunteers (ages 25 ± 3.6 yr) with normal left ventricular function were imaged as controls. All were clinically well with no signs of cardiac dysfunction.

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Sedation was achieved with chloral hydrate for children under 3 yr, and oral pentobarbital sodium and meperidine were used for children between 3 and 7 yr. For cases of inadequate sedation, intravenous pentobarbital sodium was given.

MRI

Patients were imaged using a Siemens 1.5-Tesla Magnetom magnetic resonance scanner. MRI used electrocardiographic gated, spin echo, and cine techniques. Older patients were placed in a body coil and younger patients in a head coil. Initial scans to define the cardiovascular anatomy consisted were placed in a body coil and younger patients in a head coil. Initial scans to define the cardiovascular anatomy consisted of two sets of T1 axial slices, 4–6 mm thick, depending on the size of the patient, with the interslice spacing equal to the slice thickness. The acquisitions were interleaved to yield contiguous slices. Three localizers were performed to achieve the final standardized short-axis views of the left ventricle. The first localizer imaged through the atrioventricular valve plane was done to visualize both valve orifices. The second localizer was positioned perpendicular to a line drawn between the two atrioventricular valve centers seen on the first localizer and intersecting the ventricular apex. This yielded an image of the mitral valve and the left ventricular apex in the same plane. Finally, the third localizer was positioned to intersect the mitral valve and apex of the left ventricle yielding a four-chamber view of the heart. Two slices, one one-third of the distance from atrioventricular valve (AVV) to apex and the second two-thirds the distance from AVVs to apex (denoted Apex) were chosen to undergo imaging to create two left ventricular short-axis SPAMM sequences.

Spatial Modulation of Magnetization

SPAMM imaging is performed by a sequence of timed, nonselective radio-frequency pulses of which the sum is 130° separated by a series of magnetic field gradient radiofrequency pulses that produce saturated spins in two sets of parallel stripes perpendicular to each other. This sequence is followed by a standard gradient echo sequence to achieve a grid on the myocardium dividing the tissue into cubes. Slices ranging in thickness between 5 and 8 mm are acquired for 12 equally spaced time periods (phases) beginning at end-diastole and moving through systole. Myocardial wall motion distorts the magnetic grid, and assessment of motion and deformation is made by tracking the movement of the intersection points formed by the grid lines. For each SPAMM sequence, effective repetition time = R–R interval, inversion time = 16 ms, flip angle = 30°, matrix size = 128 × 256 interpolated to 256 × 256, slice thickness range = 4–7 mm, tag thickness range = 1.5–2 mm, field of view range = 160–280, and number of excitation = 3. There were 30 ms between images.

Analysis

Images were downloaded from the Magnetom to a Sun SPARC station 10 (Sun Microsystems, Mountain View, CA) for computer analysis. Volumetric Image Display and Analysis (13), a user-interactive software package, was used to determine strain and wall motion. The intersection points formed by the perpendicular SPAMM lines were marked and tracked in series by moving the labeled points from phase to phase on successive images. A mathematical technique called Delaunay triangulation (6, 14) was then used to connect the points to create nonoverlapping, equally sized triangles. These triangles were also labeled and followed from image to image. Wall Motion (Twist and Radial Shortening)

Twist and shortening were measured relative to the centroid of the ventricular cavity at end-diastole that was determined by tracing the endocardial border and calculating the center based on those borders. The center of each triangle at each phase was then obtained by computerized counting of pixels. With the use of a Cartesian coordinate system and the following mathematical formulas, the distance (radial shortening) and the angle (twist) made by a ray from the centroid of the cavity to the center of the triangle was obtained

$$\theta = \cos^{-1}\left(\frac{(P_n - P_{n+1}) \cdot (P_n - P_{n+1})}{|P_n - P_{n+1}|}\right)$$

where $P_{n+1} - P_n$ is the distance between the centroid of the triangle and the centroid of the ventricle at phases $n$ and $n+1$ (shortening at each phase) and $\theta$ is the angle the rays make (twist at each phase). $X_n$ and $Y_n$ and $X_{n+1}$ and $Y_{n+1}$ are the coordinates of the center of the triangle at phase $n$, $X_n$ and $Y_n$ are coordinates of the centroid of the cavity, $P_n \cdot P_{n+1}$ is the vector dot product of the rays at phase $n$ and $n+1$. Radial shortening was defined as the distance moved toward the center of the ventricular cavity indexed to the diameter of the ventricular cavity (mm/end-diastolic radius in mm). Twist was defined as the amount of rotation about the center of the ventricular cavity and was measured in degrees (a positive value indicates counterclockwise twist and a negative value clockwise twist when viewed from apex to base). Data were also displayed graphically, in which end-diastole was denoted by a point and motion in systole represented by a line following the point (Fig. 1, A-C).

Strain

Strain is the unitless measurement of deformation that relates the changes in the myocardial wall shape in systole relative to end-diastole. A positive strain value signifies elongation, and a negative strain represents compression. Strain calculations use the two-dimensional strain tensor and

$$\text{strain} = \frac{\text{current shape} - \text{base shape}}{\text{base shape}}$$

and

$$\text{strain} = \frac{\text{current size} - \text{base size}}{\text{base size}}$$

where $V_{current}$ and $V_{base}$ are the current and base volume, respectively.

Fig. 1. A: short-axis image using spatial modulation of magnetization, which divides myocardium into a magnetically tagged grid. Intersection of grid lines are labeled with white points and are tracked from phase to phase. B: points are connected into triangles. C: centroid of each triangle is tracked through systole. A point represents the starting point at end-diastole, and a line represents systolic movement. D: distortion of triangles (strain) is represented by color coding.
the method of eigensystems solutions to determine the deformation of each triangle. Principal strain (\(E_1\); the parameter used in this study) always represents the largest compressive (negative) strain. Strain data were obtained by averaging the strain of all the triangles at each phase and noting the maximal compressive strain observed with its standard deviation. Strain data were also displayed in color coded or gray scale form, either alone, or superimposed on the anatomic magnetic resonance image of the ventricle (Fig. 1, A, B, and D).

Data Interpretation

The myocardium was divided into four areas (ventricular septum, inferior wall, posterior wall, and superior wall) at each of the two short-axis levels (AVV and Apex levels) to obtain regional parameters. Twist was studied by evaluating initial twist (the initial motion in 1 direction) and net twist (the sum of the total motion throughout the phases in systole). Radial shortening, as well, was analyzed as initial and net values. Values of \(E_1\) strain were analyzed in each region at both short-axis levels. Strain heterogeneity, or the distribution of strain within a region, was evaluated by calculating the standard deviation of strain divided by the average strain for each region. This ratio was compared among regions between transplant patients and normal controls.

Statistics

Only data from the first MRI scan in the patient who underwent two studies were used in the quantitative statistical analysis. Comparisons between groups were made using Student’s t-test. Comparisons between multiple groups were done with analysis of variance. All measurements are recorded as the means \(\pm SD\), and differences between values represent differences in the geometric means. Significance is defined as \(P < 0.05\).

RESULTS

Twist Analysis

Qualitative analysis. Normal control subjects had counterclockwise twist in all regions (Fig. 2, left). Although there was some diversity in the transplant patients patterns of wall motion, there were a few unifying themes. Six of eight studies had clockwise twist of either the superior, inferior, and/or posterior wall (the two studies that did not have a wall with clockwise twist were from patient 1, who underwent 2

<table>
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<th>VS</th>
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| AVV, atroventricular valve; VS, ventricular septum; IW, inferior wall; PW, posterior wall; SW, superior wall; Ak, akinetic; CW, clockwise; CCW, counterclockwise; NTw, no twist; Pd, paradoxical.

MRI scans 1 yr apart). All studies had regions of no twist (i.e., direct linear movement toward the left ventricular centroid). Six studies had akinetic regions (posterior wall in 1, ventricular septum in 2, inferior wall in 2, and ventricular septum and inferior wall in 1), and one had paradoxical wall motion of the ventricular septum (Table 1 and Fig. 3, left). The patient who was imaged twice had minor twist abnormalities in his first study (regions of no twist at the posterior wall) and similar findings 1 yr later (Table 1, patients 1A and 1B).

Quantitative analysis. COMPARISON WITHIN PATIENT SUBTYPES. Transplant patients revealed no significant difference in initial or net twist among the four regions at the AVV and no differences in initial twist at the Apex. There was a difference in net twist (\(P < 0.02\)) among the four regions at the Apex (net twist was smaller at the inferior wall). Normal controls had no significant difference in initial or net twist among the four regions at both short-axis levels. Radial shortening in transplant patients demonstrated that initial and net shortening were both different among the four regions at the AVV (\(P < 0.01\) for initial, and \(P < 0.05\) for net shortening) and Apex (\(P < 0.05\) for both initial and net shortening). For both short-axis levels, the ventricular septum had less initial and net shortening than the
other regions. Normal controls had differences only in initial shortening at the AVV (P < 0.05). In these patients, the superior wall had a higher initial shortening than the other regions.

**Comparison between patient subtypes.** When comparing transplant patients to the normal subjects, initial twist was different at the ventricular septum of the AVV (P < 0.05). A trend was noted for greater initial and net twist in normal subjects than transplant patients in all regions except apical superior and septal walls. This greater net twist in normal subjects reached statistical significance in net twist at apical inferior wall (*P < 0.02). VS, ventricular septum; IW, inferior wall; PW, posterior wall; SW, superior wall. Error bars, SD.

**Strain analysis. Comparison within patient subtypes.** No statistical difference in E₁ strain at the AVV and Apex was found within the four myocardial regions of both the transplant patients and normal subjects. Heterogeneity of strain within each region was not statistically different among the four regions at the AVV and Apex levels in the transplanted hearts or in the normal subjects.

**Comparison between patient subtypes.** Comparing the transplant patients with normal controls, E₁ strain was not different in any region of the AVV or Apex (Figs. 3, right, and 6, A and B) with the exception of larger E₁ strains in the control group than transplant patients at AVV superior wall (*P < 0.05). Error bars, SD.
Analysis of Abnormal Twist Regions in Transplant Patients

Regions of abnormal and normal twist were selected qualitatively (graphic data) and confirmed quantitatively (a significant difference in twist between the 2 regions in degrees; Fig. 8A) for the expressed purpose of comparing strain and shortening between these two regions. It was prespecified that if the qualitative analysis did not agree with the quantitative data, then we would not proceed with the comparison. All qualitative analyses did agree with the quantitative ones. Although there were differences in initial (AVV and Apex, P < 0.05) and net shortening (AVV P < 0.05, Apex P < 0.01; Fig. 8B), there was no difference in strain or strain heterogeneity between these abnormal and normal twist regions (Fig. 9, A and B).

DISCUSSION

Hansen and colleagues (11) reported in 1987 that compared with baseline, left ventricular torsional deformation amplitude and rate were altered in adult patients with ventricular dysfunction and histological evidence of rejection. Torsional deformation was determined by placing intramyocardial radiopaque markers in the transplanted hearts and viewing them with fluoroscopy. Compared with their prerejection data, the torsional deformation in the maximally deforming segment (denoted \( \theta_{\text{max}} \)) decreased by 25% during acute rejection and myocardial necrosis. This was associated with a significant decrease in the torsional rate (\( \text{d} \theta_{\text{max}}/\text{d}t \)). Left ventricular end-diastolic volume, stroke volume, ejection fraction, peak left ventricular filling rate, and diastolic recoil did not change during the rejection episode. These findings are the driving force behind this initial pilot study. Because the biomechanics of the transplanted left ventricle have numerous reasons why they should not be the same as those of the normal left ventricle (see introduction), this study attempted to define twist, radial shortening, and strain in the pediatric transplanted left ventricle in the baseline state. The findings should be viewed as hypothesis generating because of the small number of patients and comparisons to young adult left ventricles. If these data are confirmed by larger numbers of patients and pediatric controls, it will add to our understanding of cardiac transplantation and form the basis of a potential way to more definitively determine rejection noninvasively.

Twist and Strain

MRI using SPAMM to assess twist in normal left ventricles was first described by Young et al. (16). This technique goes further than the ones previously described (3, 10, 11), because regional events may be easily examined in addition to global parameters. A recent study showed that regional area strain correlates with regional oxygen consumption in certain instances (9). Measurements of myocardial strain have been determined in the normal adult left ventricle.
using MRI and SPAMM (16). In studies from our institution (7, 8), SPAMM has been used to quantify strain in a number of congenital heart lesions. In this study, we found that even in the baseline state, pediatric transplant patients have significant abnormalities. This information gives us insight into the biomechanical properties of the transplanted heart. Once twist, radial shortening, and strain are determined in pre-versus postrejection states, correlation with histological rejection can be attempted.

Our results

This study was designed to evaluate the biomechanics of the transplanted left ventricle in a nonrejection state and then compare the results with normal subjects. Data revealed that all patients had evidence of markedly abnormal twist. Despite this finding, E1 strain and heterogeneity of strain were similar within all regions at the AVV and Apex levels and not different from the normal controls. These results demonstrate that the transplanted left ventricle seems to maintain normal strain in the presence of abnormal twist.

It is unclear what factors may be causing these alterations in twist. It has been noted in transplanted primate hearts with rejection that in the same heart, there are regions of both myocardial necrosis and regions that are relatively spared from disease (12). Focal areas of fibrosis may play a role in causing abnormal wall motion in the nonrejected state, but this remains unknown.

The catheterization and biopsy data were normal in the patients without clinical evidence of rejection, and ventricular depolarization abnormalities seen on electrocardiogram did not correlate with twisting patterns. We speculate that the regional wall motion abnormalities may be a compensatory mechanism to maintain normal strain and hemodynamic parameters in the presence of characteristics unique to the transplanted heart such as loss of sympathetic control, focal fibrosis from the period of ischemia prior to transplantation, effects of immunosuppressant drugs, or sequelae from past episodes of cellular rejection.

From our experience, we have found that the transplanted left ventricle, in general, have a thicker myocardium and smaller cavity volume relative to the myocardial mass than normal individuals (compare Figs. 2 and 3). However, one would expect this concentric, symmetrical myocardial hypertrophy to have a “global” effect on cardiac mechanics, not the regional effect seen in our study. Nevertheless, this is a possibility and should be kept in mind when considering our results.

Limitations

Comparisons of regional strain and wall motion in this study were made to adults with normal left ventricular function. We have imaged two pediatric patients with vascular ring anomalies (ages 1.1 and 1.3 yr) to determine whether there are important differences that occur with age. Their twist data appear qualitatively to be the same as the adult controls. Another limitation of this study is that correlation of the findings with endomyocardial biopsy is imprecise in that the sample is taken from the right ventricular septal surface and may not reflect the overall histological findings in the left ventricle. Finally, this study involves a small number of patients. A multicenter study would be ideal to enable quantification of the differences in strain and regional wall motion in transplant patients to determine whether these biomechanical properties change with time and/or episodes of rejection.

Perspectives

Although it is tempting to place the transplanted heart in the same category as a normal heart, there are multiple reasons, as previously stated, why this should not be so. Our data, which suggest alterations of twist in the presence of normal strain in the transplanted pediatric left ventricle when compared with the normal adult left ventricle, add another layer of complexity to the whole cardiac transplantation philosophy. If our data can be replicated in comparison with the normal pediatric left ventricle, they would imply that even in a

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**Table 2. Catheterization and biopsy data**

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<th>PAP, mmHg</th>
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LVEDP, left ventricular end-diastolic pressure; PAP, pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; CI, cardiac index; NL, normal. *Normal range for systolic pulmonary pressure is 11–36 mmHg (Vargo, T. A. Cardiac catheterization—hemodynamic measurements. In: The Science and Practice of Pediatric Cardiology, edited by Garson, A., J. T. Bricker, and D. G. McNamara. Philadelphia, PA: Lea and Febiger, 1990, p. 916). †Peak systolic systemic blood pressure = 129 mmHg; ‡Calculation is based on oxygen saturation data using the Fick equation. By the thermodilution technique, cardiac index = 3.71·min⁻¹·m⁻².
transplanted heart that is not undergoing rejection, twist is uncoupled from strain. This would add to our understanding of the biomechanics of these ventricles and has implications for using twist as a marker during rejection (obviously, the altered baseline twist must be considered).

It must be remembered that our data are only “snapshots in time” in the life of a transplanted left ventricle. Although strain measurements did not appear altered, it may be useful to investigate these parameters throughout the life of the transplanted left ventricle and certainly during rejection episodes. The noninvasive nature of MRI makes it ideal to evaluate these biomechanical properties in the hopes of finding a noninvasive surrogate to cardiac catheterization and biopsy for transplant rejection.

The transplanted heart in the baseline state has abnormal twist yet maintains similar strain patterns compared with the normal left ventricle. Further evaluation is needed to determine if there are clinically important sequelae that result from alterations in twist and whether these abnormalities progress or resolve with time. If changes in left ventricular regional strain and wall motion determined by MRI and SPAMM are important sequelae that result from alterations in twist and whether these abnormalities progress or resolve with time. If changes in left ventricular regional strain and wall motion determined by MRI and SPAMM are considered.

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