Significance of Mechanical Alterations in Single Ventricle Patients on Twisting and Circumferential Strain as Determined by Analysis of Strain from Gradient Cine Magnetic Resonance Imaging Sequences

Uyen T. Truong, MDa, Xiaokui Li, MDb, Craig S. Broberg, MDb, Helene Houle, PhDc, Michael Schaal, MDb, Muhammad Ashraf, MDb, Philip Kilner, MDd, Florence H. Sheehan, MDc, Craig A. Sable, MDa, Shuping Ge, MDc, and David J. Sahn, MDab,*

Preliminary speckle-tracking echocardiographic studies show that patients with single ventricles (SVs) have significantly decreased twisting and dyssynchrony of twisting. This could be related to abnormal cardiac looping, which leads to hearts that lack helical fiber patterns. The aim of this study was to analyze gradient cine magnetic resonance imaging (MRI) using Velocity Vector Imaging to assess cardiac mechanics. Subjects were 38 patients (aged 8 to 37 years) with SVs of left ventricular (n = 30) and indeterminate (n = 8) type who underwent cardiac MRI. Controls were 14 normal children and adults. Gradient cine MRI sequences close to the apex were subjected to a Velocity Vector Imaging analysis program adapted for MRI. In the control group, mean circumferential strain was −18.02 ± 7.31%, mean dispersion of peak circumferential strain was 44.23 ± 37.14 ms, and average rotation was −7.7 ± 1.38°. The rotation values were negative, or counterclockwise. In patients with SVs, mean circumferential strain was −8.87 ± 7.30%, mean dispersion of peak circumferential strain was 181.55 ± 76.07 ms, and average rotation was −2.6 ± 1.24° (p <0.001). Mean dispersion of the peak of rotation in the control group was 39.6 ± 22.8 ms, compared to 166.5 ± 72.4 ms in patients with SVs. In conclusion, this study showed a dramatic decrease in apical rotation and circumferential strain in the SV group compared to the control group. Strain and rotation mechanics at the apex in patients with SVs showed marked dyssynchrony. © 2010 Elsevier Inc. All rights reserved. (Am J Cardiol 2010;105: 1465–1469)

Speckle-tracking analysis has shown, in a preliminary study from our laboratory published in abstract form,1 that echocardiographic images of single ventricles (SVs) show decreased rotation and dyssynchrony of twist. The aim of this study was to assess the strain and rotational deformation in patients with SVs of left ventricular or indeterminate type compared to normal hearts using a speckle-tracking program, Velocity Vector Imaging (VVI; Siemens Medical Solutions USA, Inc., Mountain View, California), applied to magnetic resonance imaging (MRI) cines. We were the first to validate the VVI program applied to MRI in normal hearts.2 This is the first report of this technique being applied to gradient magnetic resonance images of patients with SVs.

Methods

Our study was a multicenter study and included MRI studies obtained at Oregon Health & Science University (Portland, Oregon), The Royal Brompton National Heart and Lung Hospital (London, United Kingdom), Texas Children’s Hospital (Houston, Texas), and the University of Washington (Seattle, Washington). We included patients with SVs that were of left ventricular or indeterminate type who had undergone cavopulmonary anastomosis procedures. Our controls were patients with normal hearts. The institutional review board at Oregon Health & Science University approved the study. For studies sent to us from outside institutions, patients’ identifications had been replaced by numeric codes.

The speckle-tracking program, VVI, was applied to the magnetic resonance images. VVI is commercially available for the analysis of 2-dimensional echocardiographic images, but not for magnetic resonance images. Here, the VVI analysis program used was adapted for MRI mechanical function. All magnetic resonance images were acquired using an electrocardiographically gated 1.5- or 3.0-T magnet. Depending on the center at which the images were acquired, the images were obtained with Intera 3T (Philips Medical Systems, Andover, Massachusetts) or GE Healthcare (Milwaukee, Wisconsin) systems. At 1.5 T, the cine sequences were run in steady-state free precession mode, while at 3 T, the images were acquired in conventional gradient-echo mode, without steady-state free precession mode. The gradient-echo cine loop images were converted from Digital Imaging and Communications in Medicine to...
Audio Video Interleave format and were analyzed using the VVI myocardial method.

Short-axis MRI sequences were used. Images were acquired at frame rates of 15 to 25 frames/s. VVI was applied to gradient cine MRI sequences close to the apex for the SV and control groups. The endocardial borders of the SVs in the subjects and the left ventricles of the controls were traced manually in end-diastole (Figures 1 and 2). VVI parameters were generated for 6 radial segments, as is standard for VVI, of the ventricles. These parameters included circumferential strain, rotation, and time to peak for both. The average of each parameter was compared between the SV and control groups.

Results

Cardiac magnetic resonance images of SVs after cavo-pulmonary anastomosis were analyzed. Thirty-eight children and adults made up this group, aged 8 to 37 years (mean 18). The control group was composed of 14 patients (mean age 22 years). The percentages of men in the SV and control groups were 60% and 50%, respectively.

MRI short-axis cines were analyzed by VVI near the apical level. For the control group, mean circumferential strain was $-18.0 \pm 7.3\%$, whereas for the SV group, mean circumferential strain was reduced to $-8.9 \pm 7.3\%$ (p <0.0001; Figure 3). Mean dispersion of peak circumferential strain was $44.2 \pm$
37.1 ms in the control group and 181.6 ± 76.1 ms in the SV group (Figure 4).

Average rotation was reduced from −7.7 ± 1.4° in the control group to −2.6 ± 1.2° in the SV group (Figure 3). The mean dispersion of peak rotation was 39.6 ± 22.8 ms in the control group, compared to 166.5 ± 72.4 ms in the SV group (Figure 4).

Discussion

Speckle tracking has emerged as a noninvasive, angle-independent technique to determine ventricular deformation, circumferential strain, circumferential strain rate, and tissue velocity. The measurement of global and regional function can be determined by analyzing 2-dimensional echocardiographic images. Speckle tracking on echocardiographic images to measure strain has been validated against tagged MRI techniques.

Speckle tracking offers an alternative method to determining function in patients with SVs. This technique would allow for monitoring hemodynamic changes after each stage of surgical palliation and offer insight into the risk factors that affect ventricular function. Myocardial velocity and strain by speckle tracking are volume independent. Because the volume load on the heart changes significantly after each stage of palliation of the SV, this is a critical tool for tracking the postsurgical changes in myocardial mechanics. Speckle-tracking data can be compared in the same patient before and after each stage of palliation to determine how altering the hemodynamics changes the rotational and strain mechanics of the ventricle.

In this study of speckle tracking applied to gradient cine MRI sequences, we found that SV mechanics, including strain and rotational motion, were significantly decreased compared to the normal heart. Rotational motion and strain
of the left ventricular myocardium are important components of ventricular performance. Impaired measurements of the 2 parameters have been reported in patients with hypertrophic and dilated cardiomyopathy, acute transplant rejection, and myocardial infarctions. In addition, the SVs in our study appeared to have marked dysynchrony. Our finding of significant differences in the rotation and strain mechanics of the SVs has tremendous implications for the management of patients with SVs.

Future studies may facilitate comparison of strain and rotational mechanics between SVs of left ventricular type and those of right ventricular type. Clinically, it appears that patients with left ventricular–type SVs have improved outcomes after total cavopulmonary anastomosis, which may be related to the strain mechanics and ventricular twist. A study comparing single right ventricles to systemic right ventricles in patients with transposition of the great arteries suggests that the lack of the left ventricle diminishes the function of the right ventricle. In healthy subjects, speckle tracking has shown distinct apical rotation between the left ventricle and right ventricle, with the left ventricle showing a uniform rotation and the right ventricle showing a more heterogeneous motion. We hope to correlate clinical parameters in patients with SVs, including medication, with VVI parameters in future studies. In addition, we hope to be able to subcategorize the SVs on the basis of ventricular morphology.

The study of strain also has implications for diastolic function. VVI offers an additional modality for assessing the diastolic phase of the cardiac cycle. Our study suggests a loss of rotational displacement in patients with SVs. The decrease in the magnitude and synchrony of rotational motion, if it is a surrogate for torsion, might mean that less stored torsional energy at end-systole is available for release to aid early diastolic filling.

Nonsurvivors were not included in this study. This eliminated a subset of patients with potentially worse outcomes, who might have had hemodynamic parameters distinctively different from our SV group. This group encompasses those with significant dysynchrony requiring pacemakers and those with significant arrhythmias restricting the ability to use electrocardiographically gated MRI. The lack of these patients in our patient group significantly limits our study to patients with SVs without electrophysiologic complications.

VVI adapted to MRI is based on grayscale images and is therefore highly dependent on the signal quality of the images. Variations in the quality of the magnetic resonance images may affect the accuracy of our data. Higher frame rates would also improve tracking and therefore accuracy. Speckle tracking on magnetic resonance images at a frame rate of 30 frames/s has been demonstrated to generate strain data that correlate with tagged MRI. Other methods using MRI, such as spatial modulation of magnetization tagging and velocity- and strain-encoded as well as displacement-encoded MRI, can also be used to delineate rotation and strain. These, however, require special expertise to obtain and analyze.

Our study was limited by the small size of the study groups. The magnetic resonance images included in our study were obtained from patients aged >8 years to avoid the need for sedation. Despite its limitations, our study provides a method that can be adapted for retrospective and serial evaluation of cardiac mechanics from commonly used gradient cine MRI studies obtained in patients with congenital heart disease, including those in patients with SVs.


