Left Ventricular Rotational Mechanics before and after Exercise in Children

Michael V. Di Maria, MD, Giuseppe Caracciolo, MD, Steven Prashker, MS, Partho P. Sengupta, MD, and Anirban Banerjee, MD, *Philadelphia, Pennsylvania; New York, New York; Ottawa, Ontario, Canada*

Background: In children, there is limited information regarding the relative contribution of left ventricular (LV) apical and basal rotation to increase LV pump function with exercise. The aim of this study was to test the hypothesis that a progressive increase in LV pump function with exercise is related to increased LV apical and basal rotation.

Methods: Forty-two subjects 12 to 18 years of age with normal cardiac structure and function were recruited prospectively and imaged at rest, and in 20 subjects, imaging was repeated after moderate exercise. Conventional measures of LV systolic and diastolic performance were evaluated. Left ventricular rotation, LV twist, rotational rate, and recoil and untwist rates were measured using two-dimensional speckle-tracking echocardiography. Torsion was calculated by normalizing LV twist to LV diastolic length. Twist displacement loops were constructed from data obtained at rest and after exercise.

Results: Apical rotation increased significantly after exercise ($7.33 \pm 2.8°$ vs $11.6 \pm 4.7°$, $P = .0004$), but basal rotation did not (-4.85 ± 1.9 vs -6.46 ± 4.81, $P = .21$). Similarly, peak twist, torsion, and twist rate also increased significantly after exercise. In diastole, apical recoil rate and LV untwist rate also increased significantly with exercise. The slope of the systolic limb of the twist displacement loop and the area enclosed by the loop also increased significantly with exercise.

Conclusions: Increases in global LV pump function during exercise in children are associated with enhanced LV apical rotation but not LV basal rotation. In addition, unique changes were seen in twist displacement loops in children before and after exercise. These data may serve as a foundation for understanding future applications of LV rotational mechanics in disease states. (J Am Soc Echocardiogr 2014;■:■-■.)

Keywords: Left ventricular mechanics, Torsion, Exercise

The helical arrangement of left ventricular (LV) myofibers results in a twisting motion along the left ventricle's long axis during systole, during which blood is "wrung out" of the ventricle. During early diastole, kinetic energy that has been stored in elastic fibers in the ventricular wall generates transmitral suction as the ventricle untwists.[1,2] With the advent of speckle-tracking echocardiography (STE), LV rotational mechanics can now be measured at the patient's bedside, and this technique has been validated by comparison with tagged magnetic resonance imaging.[3] The utility of STE lies in its high degree of sensitivity and thus in its ability to detect subtle changes in myocardial deformation that precede changes in shortening fraction or ejection fraction.[4]

Despite the broad application of this novel technique in adults, very little has been published on the subject of LV rotational mechanics in children.[5] Preliminary data in children, using tissue Doppler, revealed that the base and apex of the left ventricle both rotate counterclockwise in infants; beginning in the preadolescent time period, the base begins to rotate increasingly clockwise until the adult pattern is attained.[6] However, unlike tissue Doppler, STE is not angle dependent and has emerged as the preferable modality for measuring LV rotation.

Combining the measurement of LV twist with simultaneous measures of radial displacement at the base of the heart, a twist displacement loop can be plotted.[7] The twist displacement loop, therefore, incorporates both measurements of radial shortening and rotational motion. This may provide useful physiologic insight into LV rotational mechanics. The systolic portion of the twist displacement loop has been shown to be linear in the resting state in adults.[8] Studies in adults have also documented changes in rotational mechanics that take place with exercise,[9,10] showing concomitant increases in both apical and basal rotation. However, the effect of exercise on twist displacement loops has been studied quite infrequently, even in adults. Before the present study, changes in twist displacement loops and LV rotational mechanics with exercise had not been documented in children.

From The Cardiac Center, The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania (M.V.D., A.B.); the Division of Pediatric Cardiology, The Perelman School of Medicine at The University of Pennsylvania, Philadelphia, Pennsylvania (M.V.D., A.B.); the Division of Cardiology, Mount Sinai School of Medicine, New York, New York (G.C., P.P.S.); and Carleton University, Ottawa, Ontario, Canada (S.P.).

Reprint requests: Anirban Banerjee, MD, The Children's Hospital of Philadelphia, Division of Cardiology, 34th and Civic Center Boulevard, Philadelphia, PA 19104 (E-mail: banerjeea@email.chop.edu).

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Abbreviations

LV = Left ventricular

STE = Speckle-tracking echocardiography

Our investigation had two principal aims: (1) to describe changes that occur in LV rotational mechanics with moderate-intensity exercise and (2) to determine the relative contribution of the LV apex and base to increasing LV pump function with exercise. To answer these questions, we studied LV rotation, rotation rate, twist, and twist displacement loops in children before and after exercise. We also sought to describe the effect of exercise on the slope of the systolic limb and the area of the twist displacement loop, a phenomenon not studied either in adults or in children. We hypothesized that LV twist, which is inclusive of LV apical and basal rotation, would increase with exercise in children, as a result of an increase in both apical and basal rotation. Moreover, the slope of the twist displacement loop would become steeper and the area enclosed by the loop would become larger with exercise.

METHODS

Patient Population

Subjects were recruited prospectively from the population of children being evaluated in the echocardiography laboratory for routine indications such as chest pain, syncope, and murmur at the Cardiac Center of the Children's Hospital of Philadelphia. The study was approved by the Institutional Review Board of the Children's Hospital of Philadelphia. Forty-two subjects were included in the study, for whom data obtained at rest are presented. Subjects were approached for inclusion in the study if, at the conclusion of their clinically indicated echocardiographic examinations, there was normal cardiac structure and function. Subjects were excluded in the presence of anatomic abnormalities, shortening fraction $< 30\%$, significant valvar insufficiency or stenosis, or nonsinus rhythm or if there was concern for elevated pulmonary arterial pressure (on the basis of ventricular septal flattening at end-systole or a tricuspid regurgitant jet > 3 m/sec). Each subject was asked if he or she would consent to performing moderate-intensity exercise and subsequent reimaging. Twenty subjects agreed to perform exercise, and data obtained after exercise are presented for this group. Inclusion criteria consisted of age between 12 and 18 years and historically normal exercise capacity with no contraindication to moderate-intensity exercise. Subjects were also excluded if the image quality at rest or after exercise precluded adequate analysis.

Techniques

Anthropometric data were obtained from the clinical record, including weight, height, and blood pressure. Complete transthoracic two-dimensional echocardiography was performed on all subjects using the commercially available iE33 ultrasound system (Philips Medical Systems, Andover, MA). Measurements included LV wall thickness and dimensio by M-mode imaging. LV volumes and ejection fraction were measured using Simpson's biplane method.[11] Pulsed-wave Doppler was used to measure mitral valve inflow velocity, aortic outflow velocity, and the timing of aortic valve closure, and tissue Doppler was used to measure the medial septal annular velocity from the apical view.

Images of the base of the heart were obtained at the level of the mitral valve leaflet tips, and images of the apex were obtained at the furthest apical extent of the LV cavity, just proximal to the level of cavity obliteration.[12] Three to five beat clips were recorded from the parasternal short-axis view at the base and apex of the heart. The frame rate was >70 Hz. Subjects were asked to perform repeated straight leg raising to approximately 20 inches above the bed from the hip with full extension of the knee, to elevate their heart rate by ≥40 beats/min above their baseline; in a typical subject, this involved approximately 100 to 120 repetitions. After exercise, short-axis images of the apex and base were obtained in a left lateral decubitus position during transient breath holding at end-expiration, as detected by visual inspection. If the heart rate decreased rapidly between apical and basal image acquisitions, subjects were asked to briefly exercise again to increase the heart rate to equivalent levels. This was an advantage of this technique.

STE

Images were stored in digital cine-loop format for offline analysis by vendor-customized two-dimensional Cardiac Performance Analysis software (TomTec Imaging Systems, Munich, Germany), which uses speckle-tracking echocardiographic technology for angle-independent measures of two-dimensional strain. A region of interest was defined; the boundaries included the epicardial and endocardial surfaces. Because the loops were acquired using an electrocardiographically gated acquisition protocol, speckle-tracking analysis started with the R wave on the electrocardiogram. The analysis by the TomTec system is triggered by the R wave, and this has been previously validated using sonomicrometry and magnetic resonance imaging.[13] The software then tracked the two-dimensional speckles and generated waveforms. Waveforms and their corresponding cine images were inspected visually to confirm accurate tracking. The TomTec system also allows the superimposition of M-mode tracings directly over the basal rotation and radial displacement waveforms. Therefore, this provides information on rotation and displacement occurring at the point of opening of the mitral valve seen from basal views.

Definitions

LV rotation, rotation rate, recoil, recoil rate, and radial displacement were directly measured using speckle-tracking echocardiographic software from short-axis views of the LV apex and base.[14]

Rotation was defined as circumferential rotation around the long axis of the left ventricle during systole (in degrees), and rotation rate was the speed at which rotation occurred (in degrees per second). Recoil was defined as the opposite of rotation, movement returning the myocardium to its starting position (in degrees), and recoil rate was the velocity at which recoil occurred (in degrees per second). Radial displacement was defined as movement toward the centroid (in millimeters).

Figure 1 depicts apical rotation, basal rotation, and twist plotted against time over the course of one cardiac cycle. From these measured parameters, the following calculated parameters were derived[14]:

Net twist angle (referred to as "twist") = apical rotation − basal rotation (°)
Torsion = twist/LV length (°/cm)
Twist rate = apical rotation rate − basal rotation rate (°/sec)
Untwist rate = apical recoil rate − basal recoil rate (°/sec)

To reduce confusion with nomenclature, we wish to point out that the term "twist" in this study is the same as the term "net LV twist angle" described in the American Society of Echocardiography consensus document by Mor-Avi *et al.*[14] The term "recoil" proposed by us is the