The Assessment of Atrial Function in Single Ventricle Hearts from Birth to Fontan: A Speckle-Tracking Study by Using Strain and Strain Rate

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Background: Single ventricle (SV) exercise performance is impaired and limited by reduced ventricular preload reserve. The atrium modulates ventricular filling, and enhancement of atrial compliance can increase cardiac performance. We aimed to study atrial mechanics in SV hearts across staged surgical palliation compared with healthy children by using novel speckle-tracking echocardiography techniques.

Methods: A cross-sectional study of 81 patients with SV (1 day to 6.5 years) at 4 stages of surgical palliation (presurgery, 22; prebidirectional cavopulmonary anastomosis, 23; pre-Fontan, 22; post-Fontan, 14). The dominant atrium was assessed with speckle-tracking echocardiography for active (ε_{act}), conduit (ε_{con}), and reservoir (ε_{res}) strain; strain rate (SR); and $\varepsilon_{act}/\varepsilon_{res}$ ratio before each stage of surgical palliation. Findings were compared with the left atrium of 51 healthy children (1 day to 5.5 years).

Results: Single ventricle atrial size was increased ($P < .01$), and atrial ε_{res} was decreased ($P < .01$) compared with healthy controls. SV atrial ε_{con} ($P < .01$) and SR_{con} ($P < .0001$) was decreased, increased ε_{act} persisted ($P < .05$), and $\varepsilon_{act}/\varepsilon_{res}$ was increased ($P < .001$) between surgical stages. Although the expected maturational trend of increasing ε_{con}, decreasing ε_{act}, and $\varepsilon_{act}/\varepsilon_{res}$ occurred in SV, they lagged behind healthy maturational changes ($P < .0001$).

Conclusion: Single ventricle atrium is dilated, has deceased compliance, decreased early diastolic emptying, and increased reliance on active atrial contraction for ventricular filling. This deviates from normal early childhood maturational changes and appears to parallel those of an atrium facing early ventricular diastolic dysfunction. (J Am Soc Echocardiogr 2013;26:756-64.)

Keywords: Hypoplastic left heart syndrome, Atrial strain, Speckle-tracking echocardiography, Atrial function, Single ventricle

The exercise performance in most patients after completion of staged palliation for functionally single ventricle (SV) heart disease is impaired. Results of invasive studies have shown that it is the loss of ventricular preload reserve rather than detrimental changes in afterload, contractility, or chronotropy that is the main determinant for poorer exercise performance.[1,2] In Fontan patients, the ventricular preload is limited by both its ability to enhance the passive return of venous blood through the conduit and the pulmonary vascular bed to meet demands during exercise.[3] Current strategies to improve the efficiency of the Fontan circulation have centered on research to modify surgical reconstruction of the anastomosis[4] and medical strategies to modulate pulmonary vascular resistance.[5]

Over the past 4 decades, the role of the atrium in modulating ventricular filling (preload) and cardiovascular performance is being increasingly recognized. The atrium acts as a distensible reservoir during ventricular systole (reservoir function), a passive conduit for pulmonary venous flow during early ventricular diastole (conduit function) and as a booster pump in late diastole (active function). Minor enhancement of atrial compliance (reservoir function) can markedly increase cardiac performance, and this effect is further amplified in the presence of elevated systemic venous resistance.[6] In the Fontan circulation, by virtue of having the pulmonary vascular bed placed in series with central venous return, the circuit's "systemic venous resistance" is increased, theoretically making the cardiac performance of the SV increasingly reliant on optimal atrial function. Literature on atrial function in SV is scarce, and understanding of the "natural" history of SV atrial function across staged palliation is limited. The objective of this study was to use speckle-tracking echocardiography (STE) to document SV atrial function at birth and at different stages of surgical palliation to provide insights into its role in SV physiology.

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Abbreviations

%active = Percentage of active atrial

4CH = 4-chamber

aFAC = Atrial fractional area change

ANVOA = Analysis of variance

BCPA = Bidirectional cavopulmonary anastomosis

BSA = Body surface area

ECG = Electrocardiogram

IVRT = Isovolumic relaxation time

SR = Strain rate

SR_{res} = SV reservoir strain rate

STE = Speckle-tracking echocardiography

SV = Single ventricle

TDI = Tissue Doppler imaging

METHODS

Population

This was a cross-sectional study, between 2007 and 2010, of patients with SV physiology at the Stollery Children's Hospital, Edmonton, Alberta, Canada, and the Children's Hospital and Medical Center, Omaha, Nebraska. Patients with functionally single left or right ventricle hearts in sinus rhythm were prospectively recruited at a single time point at any 4 surgical stages: (1) before their first procedure (presurgery): i.e., Norwood-Sano for hypoplastic left ventricle and modified Blalock-Taussig shunt for hypoplastic right ventricle; (2) before their second-stage palliation with bidirectional cavopulmonary anastomosis (pre-BCPA); (3) before Fontan completion (pre-Fontan); and (4) at post-Fontan follow-up (post-Fontan). Because this was a cross-sectional study, each patient was analyzed and included only once in the study population. All pre-BCPA echocardiograms were performed with the patient under sedation with oral chloral hydrate (60-80 mg/kg) as per our laboratory protocol. The use of a fenestrated extracardiac conduit or lateral tunnel to complete the Fontan circuit was at the discretion of the operating surgeon. Patients were excluded if they had a paced rhythm or inadequate images for atrial analysis. For controls, we recruited healthy volunteers (1 day to 5.5 years) who were divided into 4 age groups similar to the 4 different stages to represent normal maturational changes. All controls had no history of cardiac pathology, significant respiratory disease, or a family history of cardiomyopathy. They had a normal physical examination, 12-lead electrocardiogram (ECG), and echocardiogram. Both institutional research ethics boards approved this study, and written informed consent was obtained from legal guardians of the patients.

Two-dimensional Echocardiography

The ECGs were performed on Vivid 7 ultrasound systems (GE Medical Systems, Milwaukee, WI) with ECG and respiratory tracings, after the laboratories protocol for SV function. The protocol included two-dimensional grayscale images captured in the apical "4-chamber" (4CH) plane optimized for higher frame rate (102 ± 33 Hz), which visualizes the dominant ventricle and atrium for offline analysis.

Conventional and Tissue Doppler Imaging Parameters

In SV hearts, we assessed the dominant ventricle and the associated atrium, whereas, in controls, we assessed the left atrium and the left ventricle for diastolic function. The atrium and ventricle were assessed for size and function by using selected parameters from current pediatric recommendations.[7] They included but were not limited to (a) atrial area in end systole (A_{max}) and end diastole (A_{min}) indexed to body surface area (BSA), (b) atrial fractional area change (aFAC), (c) pre-atrial contraction area (A_{preP}) traced at the onset of the p wave on ECG, and (d) color tissue Doppler imaging (TDI) annular velocities at the lateral wall of the dominant ventricle.

Atrial Deformation Analysis by Using STE

The dominant atrium in SV and the left atrium in controls was analyzed offline by using EchoPAC version 7.1 software (GE Medical Systems) for global strain and strain rate (SR). Measurements were accomplished by the following steps. (1) A single cardiac loop at end expiration from the 4CH view was selected. (2) The 'zero' strain reference for atrial deformation analysis was set at the onset of the ECG p wave to allow clear identification of the active atrial contraction and passive emptying component (Figure 1). (3) Atrial endocardium was traced from the atrioventricular junction at the lateral free wall, along the atrial freewall, by excluding the atrial appendage, across the atrial roof and down the interatrial septum and ending at the atrioventricular septal junction. Because most SV atria have an obligatory interatrial septal defect to allow shunting of either systemic or pulmonary venous blood to the dominant ventricle, the tracing would continue across the defect in a straight line through to the septal annulus of the ventricle (Figure 2). The speckle-tracking region of interest was then adjusted to fit the atrial wall thickness before the automated tracking algorithm was applied. A review of tracking performance was made to ensure accurate tracking of the atrial myocardium. If required, further adjustment to the region of interest was made before the tracking algorithm was reapplied. (4) When satisfactory tracking was achieved, the global strain (ε) and SR – time plots were displayed for manual measurements. The corresponding peak atrial negative, ε_{act} = global atrial active strain, a measure of atrial active contraction; peak positive, ε_{con} = conduit strain, a measure of atrial early diastolic emptying and total ε_{res} = reservoir strain (calculated by $\varepsilon_{con} - \varepsilon_{act}$), a measure of atrial expansion (ε_{res}) (Figure 1). From the SR curve, the first negative peak after the ECG p wave, SR_{act} = global active SR, a measure of active atrial contractility, second negative peak, SR_{con} = global conduit SR, a measure of atrial passive emptying rate, and the peak positive, SR_{res} = global reservoir SR, a measure of atrial filling rate (Figure 3). Intra- and interobserver variability analysis was performed by using 10 randomly selected patients.

Statistical Analysis

Results are expressed as mean (SD) unless otherwise stated. Comparisons of continuous variables between stages were performed by using one-way analysis of variance (ANOVA) with Tukey post hoc testing for multiple comparisons. The unpaired *t* test was applied to compare SV and controls at each surgical stage. Intra- and interobserver variability was expressed as the mean percentage error and calculated by the absolute difference of the 2 measures divided by the mean of the 2 measures. Statistical significance was defined as $P < .05$. Data analysis was performed by using Prism 5 version 5.0a (GraphPad Software Inc, La Jolla, CA).

RESULTS

Study Population

Eighty-one patients with functionally single right (n = 55) or left (n = 26) ventricles were prospectively recruited at 4 surgical stages: (1) presurgery, 22; (2) pre-BCPA, 23; (3) pre-Fontan, 22; and (4)