Noninvasive Estimation of Ventricular Filling Pressures in Patients with Single Right Ventricles

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Background: Increased ventricular end-diastolic pressure (VEDP) is a known risk factor for morbidity and mortality in patients with single-ventricle physiology. Spectral Doppler tissue imaging (DTI) has been shown to modestly correlate with direct measurement of VEDP. Strain rate (SR) values, obtained via myocardial deformation, have not yet been compared with VEDP in this patient population. The goal of this study was to evaluate which of these imaging techniques correlates best with VEDP in patients with single-RV (RV) physiology.

Methods: Patients with single-RV physiology who underwent simultaneous echocardiography and catheterization were evaluated. Echocardiographic data included global longitudinal SR early diastolic wave (SRe) and SR late diastolic wave (SRa), DTI early diastolic wave (e′) and DTI late diastolic wave (a′) of the right ventricular free wall, and right atrioventricular valve inflow velocities (E and A waves). E/SRe and E/e′ ratios were calculated. VEDP was obtained from the catheterization report.

Results: Twenty-seven studies were performed on patients with single-RV physiology. The median age at the time of catheterization was 11.4 months (range, 0–132 months). The mean VEDP was 9.9 ± 4.5 mm Hg. VEDP correlated significantly with E/SRe ratio ($r = 0.88$), global SRe ($r = -0.52$), SRe/SR late diastolic wave ratio ($r = -0.42$), and valve A velocity ($r = 0.48$). There were no significant correlations between VEDP and DTI measurements. Receiver operating characteristic curve analysis using an E/SRe cutoff of 150 cm showed 87.5% sensitivity and 78.9% specificity for predicting VEDP > 10 mm Hg.

Conclusions: In patients with single-RV physiology, VEDP correlated strongly with SR but not with DTI measurements. SR measurements should be considered as a possible means to estimate VEDP in this complex patient population rather than DTI. (J Am Soc Echocardiogr 2013;26:1330-6.)

Keywords: Single right ventricle, Hypoplastic left heart syndrome, Strain rate, Tissue Doppler, Catheterization

Elevated ventricular end-diastolic pressure (VEDP) is a marker for diastolic dysfunction. Increased VEDP is known to be associated with morbidity and mortality in patients with single-ventricle physiology.[1-4] Cardiac catheterization is the gold standard used to assess VEDP in patients with single-ventricle physiology. Few studies have assessed methods of noninvasively evaluating VEDP in the single-RV (RV) population. If a noninvasive measurement could accurately estimate VEDP in the single-RV patient population, this would assist in caring for this complex population.

Menon *et al.*[5] showed modest correlations between Doppler tissue imaging (DTI) variables and pulmonary vein Doppler pattern with VEDP in patients with single-ventricle physiology. Learn *et al.*[6] also showed significant correlations between DTI values and atrioventricular valve early diastolic wave velocity with invasively measured central venous pressures after cardiac surgery in 20 patients with single-ventricle physiology. However, both these studies did not evaluate deformation values in assessing VEDP in this population.

Strain rate (SR) early diastolic wave (SRe) and SR late diastolic wave (SRa) values obtained via myocardial deformation analysis are emerging as a new technique to assess diastolic myocardial function.[7,8] Kimura *et al.*[9] showed that speckle-tracking–derived E/SRe ratios in patients with normal heart anatomy demonstrated better correlations with invasively measured ventricular filling pressures (pulmonary capillary wedge pressures) than tissue Doppler. No studies have evaluated the validity of SR in assessing VEDP in patients with single RVs.

The goal of this study was to determine which noninvasive echocardiographic diastolic parameter had the best correlation with VEDP in patients with single RVs.

METHODS

The institutional review board approved this prospective study. All consecutive patients with single RVs who underwent cardiac catheterization from 2011 to 2012 were recruited for the study. Informed consent was obtained from parents before cardiac catheterization. Assent was obtained from patients aged > 9 years. All patients with single RVs undergoing catheterization for any indication were

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Abbreviations
DTI = Doppler tissue imaging
RV = Right ventricle
SR = Strain rate
SRa = Strain rate late diastolic wave
SRe = Strain rate early diastolic wave
VEDP = Ventricular end-diastolic pressure

included. Exclusion criteria were poor echocardiographic image quality such that SR analysis could not be performed on a six-segment model of the single RV with postprocessing, absent or near absent interventricular septum that did not allow six-segment analysis in patients with the diagnosis of double-outlet RV or unbalanced atrioventricular septal defect, nonatrial rhythm, and failure to obtain consent. Thirteen patients were excluded, five for poor image quality, one for junctional rhythm, one for a missing electrocardiogram, four for absent or near absent interventricular septum, and two for incomplete catheterization data.

Echocardiographic Data

All echocardiographic studies were obtained using a Vivid I or Vivid 7 machine (GE Healthcare, Wauwatosa, WI) after the patient was under general anesthesia and just before the start of the cardiac catheterization. Frame rates were maintained at >80 frames/sec in all studies. Views equivalent to a standard apical four-chamber view were obtained (Figure 1). Images were optimized for the visualization of the epicardial and endocardial borders of the single RV. Postprocessing of all images was completed offline using EchoPAC version 10 (GE Healthcare), which obtains SR values via speckle-tracking analysis. All measurements were made in triplicate by a single observer blinded to the results of the cardiac catheterization measurements.

DTI Measurements

DTI measurements of the right ventricular free wall at the level of the atrioventricular valve annulus were obtained in the apical four-chamber view. DTI early diastolic wave (e′) and DTI late diastolic wave (a′) of the right ventricular free wall were obtained using pulsed spectral Doppler sampling in all patients. Right atrioventricular valve peak inflow velocities, early diastolic wave (E) and late diastolic wave (A), were also obtained from the same view. E/e′, e′/a′, and E/A ratios were derived from these values. Myocardial performance index was also calculated ([isovolumetric contraction time + isovolumetric relaxation time]/ejection time) using corresponding DTI values for the free right ventricular wall.

Strain Measurements

The endocardial border of the single RV in an apical four-chamber view was traced from the septal-atrioventricular annular hinge point to the apical septum and then to the right ventricular lateral wall at the lateral-atrioventricular annular hinge point. The automated epicardial-to-endocardial computer-generated border, or region of interest, was adjusted to include the epicardium. The single RV was divided automatically into a six-segment model. Borders were accepted if both visual inspection and the software indicated adequate tracking for all segments. Patients whose segments did not track well because of artifacts or inadequate visualization of the lateral borders of the RV were excluded. Longitudinal peak global SRe and global SRa were obtained on postprocessing evaluation of the global SR curve (Figure 2). Global values were obtained by averaging the

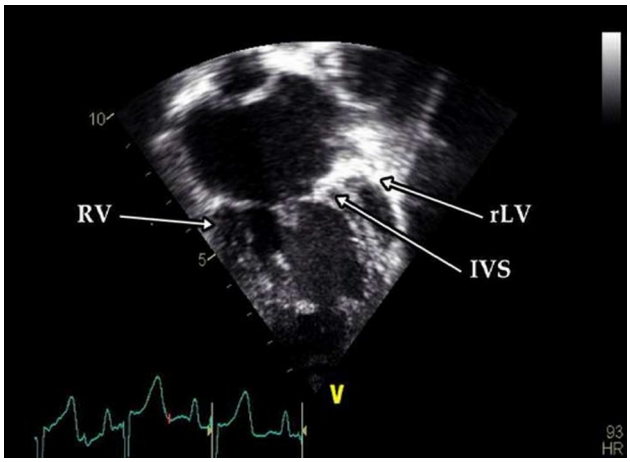

Figure 1 Apical four-chamber view of single RV. *IVS*, Interventricular septum; *rLV*, rudimentary left ventricle.

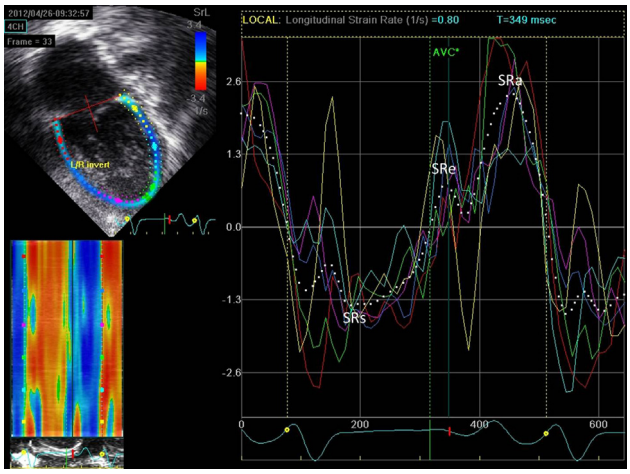

Figure 2 SR curve of a 2.5-year-old male patient with hypoplastic left heart syndrome after comprehensive stage II procedure, who presented for routine pre-Fontan cardiac catheterization. He was found to have a VEDP of 8 mm Hg.

values of six-segment model in EchoPAC. E/SRe and SRe/SRa ratios were calculated from these variables, similarly to DTI measurements.

Cardiac Catheterization

All hemodynamic measurements were performed under general anesthesia under the same steady-state conditions as for echocardiography. VEDP of the single RV was measured on the ventricular pressure tracing as the point just before the rapid rise in ventricular pressure corresponding to ventricular systole. VEDP numeric values were obtained from cardiac catheterization reports. All cardiac catheterization data were obtained before any interventional procedure was performed.

Statistical Analysis

Correlations of continuous variables with VEDP were examined using linear regression analysis and Pearson's *r* correlation coefficients. Areas under the curve with χ^2 difference tests were used to examine differences in logit models comparing E/SRe ratio $\geq$ 150 cm and