JACC: ADVANCES VOL. 5, NO. 3, 2026

ORIGINAL RESEARCH

Natural Shear Wave Elastography

A Promising Tool to Assess Myocardial Stiffness in Fontan Patients

Irene Cattapan, MD, PhD,[a,b,*] Ahmed Youssef, MD, PhD,[c,d,*] Aleksandra Cieplucha, MD,[c,e] Hannah Van Belle, MD,[c] Annette Caenen, MSc, PhD,[b,f] Thomas Salaets, MD, PhD,[g] Marta Orlowska, MSc, PhD,[b] Biagio Castaldi, MD, PhD,[a] Giovanni Di Salvo, MD, PhD,[a] Bjorn Cools, MD, PhD,[g] Werner Budts, MD, PhD,[c] Mark Gewillig, MD, PhD,[g] Jan D'hooge, MD, PhD,[b] Jens-Uwe Voigt, MD, PhD,[c,†] Alexander Van De Bruaene, MD, PhD[c,†]

ABSTRACT

BACKGROUND Noninvasive assessment of myocardial properties and hemodynamics in Fontan patients remains challenging. Natural shear wave (SW) elastography is a promising new echocardiographic modality that allows noninvasive assessment of myocardial stiffness using the velocity of naturally occurring SWs detected with high frame rate (HFR) imaging.

OBJECTIVES The objectives of the study were to document SW speed after atrioventricular valve closure (AVVC) and outflow valve closure in Fontan patients; to compare it with age-matched healthy volunteers; and to investigate the relation between SW speed, clinical features, and systemic venous pressures (SVPs).

METHODS The authors enrolled 47 Fontan patients (mean age: 19 ± 11 years, range 3-46y range: 3-46 years). For all, we acquired clinical data, conventional echocardiographic parameters, HFR parasternal long-axis views, and SVP when available (n = 30). HFR images were processed offline by extracting tissue Doppler acceleration color-coded maps of M-modes drawn in the middle of the wall related to both the inflow and the outflow valve.

RESULTS Average SW speeds were higher in Fontan patients than in healthy volunteers (5.3 ± 1.6 m/s vs 3.0 ± 0.5 m/s after AVVC, $P < 0.001$; 5.1 ± 2.0 m/s vs 3.4 ± 0.6 m/s after outflow valve closure , $P < 0.001$). Patients with Fontan circulatory failure had increased SW speed compared to well-functioning Fontan patients (6.3 ± 1.4 m/s vs 4.9 ± 1.5 m/s; $P = 0.008$). SW velocities after AVVC correlated moderately to SVP ($r = 0.55$, $P = 0.002$), whereas no other conventional diastolic parameter did.

CONCLUSIONS Our findings suggest that Fontan hearts may be stiffer than normal and that SW velocities are higher in patients with a Fontan circulatory failure. Moreover, SW speed was related to SVP. (JACC Adv. 2026;5:102608)

From the [a]Pediatric Cardiology Unit, Department of Women's and Children's Health, University Hospital of Padua, Padua, Italy; [b]Department of Cardiovascular Science, Cardiovascular Imaging and Dynamics, University Hospital Leuven, University of Leuven, Leuven, Belgium; [c]Department of Cardiovascular Science, Division of Cardiology, University Hospital Leuven, University of Leuven, Leuven, Belgium; [d]Department of Cardiovascular Medicine, Suez Canal University, Ismailia, Egypt; [e]First Department of Cardiology, Poznan University of Medical Sciences, Poznan, Poland; [f]IbiTech-bioMMeda, Ghent University, Ghent, Belgium; and the [g]Department of Cardiovascular Science, Division of Pediatric Cardiology, University Hospital Leuven, University of Leuven, Belgium. *These authors share first authorship. †These authors are both senior authors.
The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

Manuscript received October 24, 2025; revised manuscript received January 16, 2026, accepted January 16, 2026.

ISSN 2772-963X https://doi.org/10.1016/j.jacadv.2026.102608

ABBREVIATIONS AND ACRONYMS

AVVC = atrioventricular valve closure

HFR = high frame rate

MS = myocardial stiffness

MVS = mitral valve closure

OVC = outflow valve closure

SVP = systemic venous pressure

SW = shear wave

SWE = shear wave elastography

Management of patients with a single ventricle circulation remains challenging.[1] In a Fontan circulation the systemic venous return is connected to the pulmonary arteries without the interposition of a pumping chamber. Advantages of a Fontan circuit include a near normalization of the arterial oxygen saturation and abolishment of the chronic volume load on the single ventricle. However, since venous return through the pulmonary vasculature is hindered by the pulmonary impedance, this circulation creates a state of chronic systemic venous hypertension and congestion and results in decreased cardiac output, both at rest and during exercise.[2,3] Indeed, systemic venous hypertension and low cardiac output will cause ongoing end-organ damage and late attrition observed in Fontan patients.[4] This process starts at pediatric age and leads to fibrotic myocardial remodeling and circuit dysfunction[5-8] with few treatment options.[9,10]

Several studies have shown a progressive age-related increase in end-diastolic pressure in Fontan patients[11] with pulmonary capillary wedge pressure, in particular, correlating to morbidity and long-term survival.[12] However, the assessment of myocardial stiffness (MS) and filling pressures using standard echocardiographic methods is limited.[13,14] Therefore, new noninvasive echocardiography parameters to assess stiffness (and filling pressures) in these patients are needed.[15,16]

Natural shear wave (SW) elastography (SWE) is a novel echocardiographic technique for the noninvasive assessment of MS[17,18] SWE uses high frame rate (HFR) imaging to detect the natural SWs after both mitral valve closure (MVC) and aortic valve closure, thus providing information on end-diastole and end-systole, respectively.[18,19] The propagation velocity of these mechanical waves is directly related to MS.[20,21] Furthermore, Bezy et al[22] have shown that SW propagation speed reflects operational stiffness, implying filling pressures next to myocardial properties affect wave propagation speed.

The aims of our study were: 1) to assess the feasibility of natural SWE in Fontan patients; 2) to document the observed natural SW speed after atrioventricular valve closure (AVVC) and outflow valve closure (OVC) in both pediatric and adult Fontan patients; 3) to compare natural SW speed in Fontan patients with age-matched healthy volunteers from previous studies in our lab; 4) to determine how wave speed varies with age and patients clinical condition; and 5) to study whether SW velocities are related with SVP assessed invasively in the catheterization laboratory or noninvasively from peripheral intravenous lines.

METHODS

This prospective cohort single center study was conducted at the University Hospitals Leuven, Leuven, Belgium, between September 2022 and June 2023. The study was approved by the local Ethical Committee before initiating the study (S66952-B3222022000955).

STUDY POPULATION. We prospectively enrolled 47 Fontan patients (15 <12 years of age, 12 between 12-18 years of age, and 20 >18 years of age) who presented at the Department of Pediatric Cardiology or at the Department of Cardiology for scheduled cardiac catheterization or outpatients' consultations, respectively. Informed consent was obtained directly from all patients from ≥12 years of age, as well as from the parents of all minors (<18 years of age). Patients who were hemodynamically unstable, patients with poor image quality, and patients with arrhythmias other than sporadic premature beats were excluded from the study.

Findings in this population were compared to those in age-matched healthy volunteers (n = 47) who had been recruited in the context of a previous study.[23] Control subjects were either healthy volunteers from our research lab or healthy children of coworkers who were invited to be scanned at the hospital in the context of previous studies. Before enrollment, a complete echocardiography excluded anatomical of functional defects.

Medical records of all patients were reviewed for baseline data: demographics, type of congenital heart defect and surgical/interventional history, clinical characteristics (NYHA functional class, blood pressure, and resting oxygen saturation), current medical therapy, and electrocardiogram. Fontan circulatory failure was identified as the presence of one of the following conditions: patient being listed for heart transplantation, heart failure, NYHA functional class 3, protein losing enteropathy, plastic bronchitis, and increased pulmonary vascular resistance.

To test whether SWs could reflect worse Fontan hemodynamics, we considered systemic venous pressures (SVPs).[24] These data were available in 30 patients, via recent heart catheterization (n = 17) (ie up to 6 months before SWE measurement for a stable patient) or an intravenous-line cannulation (n = 13). For noninvasive recordings of pressure in the total cavopulmonary connection via intravenous lines, we followed the methodology published by

Miranda et al[25] and Cieplucha et al.[26] These data were collected on the same day of echocardiography.

CONVENTIONAL ECHOCARDIOGRAPHY. All patients underwent a standard echocardiographic assessment using an E95 echocardiography machine, equipped with a M5S-D phased array transducer (GE Vingmed). Echocardiograms were performed by 2 pediatric cardiologists. Images were then analyzed offline on EchoPAC (software version 204) by a single experienced observer. Conventional parameters of systolic and diastolic function were recorded. We used left ventricular ejection fraction by the biplane Simpson method for morphologically left univentricular hearts and fractional area change for morphologically right ventricles. Atrioventricular valve inflow and annular velocities were recorded. Ventricular strain was determined by speckle tracking from the 3 apical views for left-dominant ventricles and from the apical 4-chamber view for right dominant hearts. In addition, parameters with the predictive value of ventricular diastolic function were considered: Tei-index, pulmonary veins S/D ratio, pulmonary A wave duration, duration of pulmonary A wave minus duration of atrioventricular inflow A wave.[27,28]

HIGH FRAME RATE ECHOCARDIOGRAPHY. HFR images were acquired using the HFR image acquisition function of the same research ultrasound machine and the same clinical phased array transducer as for conventional echocardiography. Images were acquired at an average frame rate of 1,367 ± 270 frame/s in a parasternal long axis view. Since tracing of natural SWs after MVC and aortic valve closure is performed typically along the interventricular septum,[20,29,30] this is not always possible with the cardiac anatomy of single ventricles, where an intact interventricular septum does not always exist. Therefore, we considered tracking the natural waves across the ventricular septum or the anterior ventricular wall (in case of absent septum/large septal defect). As a result, for patients with tricuspid atresia, pulmonary atresia with intact interventricular septum, pulmonary atresia with septal defect, and Ebstein anomaly, we considered the interventricular septum, whereas for patients with double inlet left ventricle, hypoplastic left ventricle, unbalanced atrioventricular canal, and double inlet right ventricles, we tracked the natural SWs along the anterior free wall.

Tissue Doppler images were extracted from the HFR images and an anatomical M-mode was performed along the midline of the selected wall. Then tissue acceleration maps where derived from the M-mode where SWs appear as tilted green bands and their slope represents their propagation velocity. SWs originated by the closure of atrioventricular valve (AVVC, isovolumic contraction phase) and of the outflow valve (OVC, isovolumic relaxation phase) were identified based on electrocardiogram and B-mode images; and their wave speed was measured semiautomatically. All image processing and analysis was performed using in-house developed software (SPEQLE, KU Leuven) in Matlab R2021b (MathWorks Inc.). This process is shown in **Figure 1**.

SW speed measurements were repeated 3 times for every SW by the same reader (I.C.) and results were then averaged. Intraobserver variability (A.Y.) was assessed in 11 randomly selected cases representative of the overall cohort: 4 with right-dominant ventricles (36.4%) and 7 with left-dominant ventricles (63.6%). In 6 cases, SWs were tracked along the anterior wall and in 5 cases along the septum. Interobserver variability between 2 observers (I.C. and A.Y.) was evaluated in 10 of these 11 cases, as 1 data set was unavailable at the time of the second analysis (eg, archived data could not be retrieved).

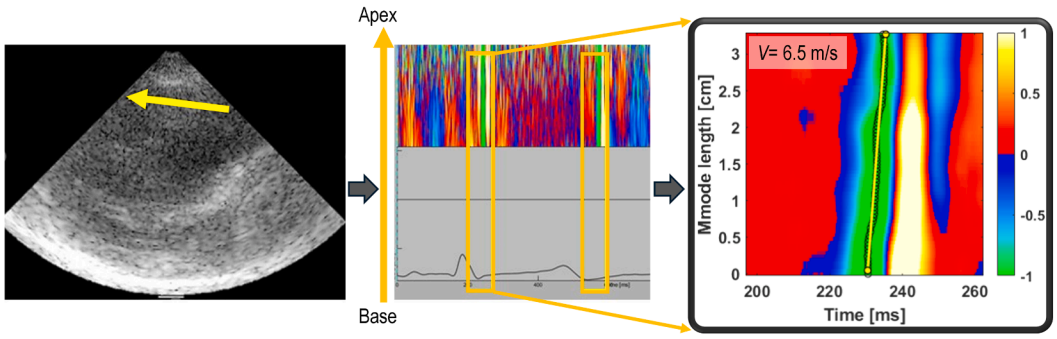
STATISTICAL ANALYSIS. Continuous variables are displayed as mean ± SD, when normally distributed, or as median and IQR. Categorical variables are presented as frequencies and percentages. Normal distribution was tested using the Shapiro-Wilk test. The association in between continuous variables was tested using Pearson's correlation for normally distributed variables and with Spearman's correlation for not normally distributed variables. Between groups comparisons were assessed through Student's t-test or Mann-Whitney test. One-way analysis of variance or Kruskal-Wallis was used if there were more than 2 groups. Associations between categorical variables were tested using the chi-square test. A 2-sided P value of 0.05 was considered statistically significant for all tests.

Intraobserver and interobserver reproducibility were evaluated using the intraclass correlation coefficient (ICC) (2-way random model, consistency between average measures). In addition, reproducibility was evaluated using the Bland-Altman analysis. All statistical analyses were performed using SPSS software (version 25.0; IBM).

RESULTS

POPULATION CHARACTERISTICS. In total, 47 patients (range 3-46y; median age 17y, IQR 18) and 47 age- and sex-matched healthy volunteers were included in this study. Vital parameters and echocardiographic features of the 2 populations are reported in **Table 1**. Among the patients, there were

FIGURE 1 SW Measurement



An example of SW measurement is shown. First, an anatomical M-mode is drawn along the midline of the selected wall. Then, a tissue acceleration map is derived from the M-mode. SWs appear as tilted green bands and their slope represents their propagation velocity. Lastly, SW speed is assessed with SPEQLE, an in-house developed software. SW = shear wave.

15 children (<12 years of age), 12 adolescents between 12 and 18 years of age, and 20 adults. Sixty-six percent of patients had a left-dominant ventricle whereas 34% had a right-dominant ventricle. Indications for Fontan palliation were tricuspid atresia (n = 12, 25.5%), double inlet left ventricle (n = 13, 27.6%), unbalanced atrioventricular septal defect (n = 5, 10.6%), hypoplastic left ventricle (n = 8, 17%), double inlet right ventricle (n = 2, 4%), pulmonary atresia with ventricular septal defect (n = 4, 8.5%), pulmonary atresia with intact septum (n = 2, 4%), and Ebstein anomaly (n = 1, 2%). The median time from Fontan palliation was 13.3 years (16.8).

Detailed clinical characteristics of the Fontan cohort are depicted in Table 2. Patients with a systemic right ventricle were on average younger than patients with a systemic left ventricle. Consequently, there was also a difference in average time since Fontan palliation. Twelve patients met our definition of Fontan circulatory failure (systolic heart failure n = 3, listed for cardiac transplantation n = 1, NYHA functional class 3 n = 3, and protein losing enteropathy n = 5). Sixty percent of patients were in NYHA functional class 1, whereas 34% were in NYHA functional class 2 and 6% in NYHA functional class 3. There were no patients in NYHA functional class 4.

CONVENTIONAL ECHOCARDIOGRAPHIC PARAMETERS. Conventional echo parameters of the Fontan cohort and healthy volunteers are reported in Table 1. When compared to healthy volunteers, Fontan patients had lower heart rates, lower systolic function, global longitudinal strain and E/A ratio, and increased E/E' ratio, isovolumetric relaxation and contraction time. Among different single ventricles anatomies, we found a slightly higher ejection fraction in morphologically left-dominant ventricles compared to a lower fractional area change in morphologically right-dominant ventricles (57 ± 7% vs 47 ± 5%; $P = 0.044$). There were no missing data for variables of interest.

HIGH FRAME RATE ECHOCARDIOGRAPHY. Feasibility of high frame rate echocardiography. SW measurements in 40 of 47 patients (85%) after AVVC and in 43 of 47 (91%) patients after OVC were included in this study. In 17/47 patients (36%) SWs were measured in the septum, whereas in 30/47 patients (64%), SWs were measured in the anterior wall. One patient was excluded due to noisy signals. Notably, at the time of AVVC, 3 SWs were observed: 1 occurring immediately before complete AVVC and 2 occurring immediately afterward with a fixed interval. The wave most closely aligned with AVVC was identified by visual assessment and confirmed using pulsed wave-Doppler timing. Six patients (13%) showed an SW traveling in the opposite direction of normal propagation after AVVC (ie apex to base) and 3 patients (6%) after OVC. This finding appeared to be independent of underlying anatomy and speed values were similar to those of waves propagating from base to apex. Nevertheless, these patients were excluded from further analysis to avoid biases due to altered wave physics, as the origin of these waves was not fully understood. Specifically, it was unclear whether they arose from different source points following the same valve-closure event, as described by Papadacci et al,[31] represented different phases of the same wave, or originated from an alternative mechanism.[32]

TABLE 1 Baseline Characteristics of Fontan Patients and Healthy Volunteers

	Fontan Patients (n = 47)	Anterior Wall (n = 30)	Septum (n = 17)	Healthy Volunteers (n = 47)	*P* Value With Fontan vs Control
Age, y	17 (10-28)	15 (9-20)	26 (13-36)[a]	19 (10-28)	0.836
Sex					0.403[b]
Male	30	19	11	25	
Female	17	11	6	22	
BSA, m^2	1.5 ± 0.5	1.4 ± 0.5	1.6 ± 0.3	1.6 ± 0.4	0.475
BMI, kg/m^2	20.6 ± 5.4	20.4 ± 6.2	20.9 ± 3.7	20.2 ± 4.4	0.682
Heart rate	81 ± 17	83 ± 20	76 ± 10	69 ± 12	**<0.001**
Systolic blood pressure, mm Hg	115 ± 13	114 ± 13	115 ± 13	115 ± 12	0.932
Diastolic blood pressure, mm Hg	68 ± 12	69 ± 14	68 ± 8	67 ± 10	0.502
Ejection fraction/FAC, %[c]	54 ± 8	52 ± 7	57 ± 8[a]	63 ± 3	**<0.001**
Ejection fraction, % (n = 32)	57 ± 7	56 ± 6	58 ± 8	63 ± 3	-
FAC, % (n = 15)	47 ± 5	47 ± 5	44	-	-
GLS, %	−17.7 ± 3.1	−17.6 ± 3.0	−17.8 ± 3.3	−20.9 ± 1.2	**<0.001**
E/A	1.5 ± 0.4	1.5 ± 0.4	1.5 ± 0.3	2.2 ± 0.7	**<0.001**
Deceleration time, ms	197 ± 75	180 (139-228)	177 (143-247)	185 ± 32	0.333
E/e′	7.6 ± 4.1	8.3 ± 4.4	6.3 ± 3.4	5.8 ± 0.8	**0.005**
IVCT, ms	87 (67-114)	96 (70-121)	81 (60-107)	67 (51-71)	**<0.001**
IVRT, ms	79 (65-96)	82 (64-97)	78 (67-91)	69 (61-78)	**0.005**
SW speed after AVVC, m/s	5.3 ± 1.6	5.0 ± 1.5	5.9 ± 1.7	3.0 ± 0.5	**<0.001**
SW speed after OVC, m/s	5.1 ± 2.0	4.6 ± 1.7	6.0 ± 2.1[a]	3.4 ± 0.6	**<0.001**

Values are mean ± SD or median (IQR); *P* values were calculated using independent sample *t*-test or Mann-Whitney test basing on distribution of variables. **Bold** indicates significant results. [a]$P < 0.05$ vs anterior wall. [b]*P* value calculated using chi-square test. [c]Ejection fraction by the biplane Simpson method was used for morphologically left univentricular hearts while fractional area change was used for morphologically right ventricles.

AVVC = atrioventricular valve closure; BMI = body mass index; BSA = body surface area; E/A = early to-late inflow velocity ratio; E/e′ = inflow to relaxation velocity ratio; FAC = fractional area change; GLS = global longitudinal strain; IVCT = isovolumic contraction time; IVRT = isovolumic relaxation time; OVC = outflow valve closure; SW = shear wave.

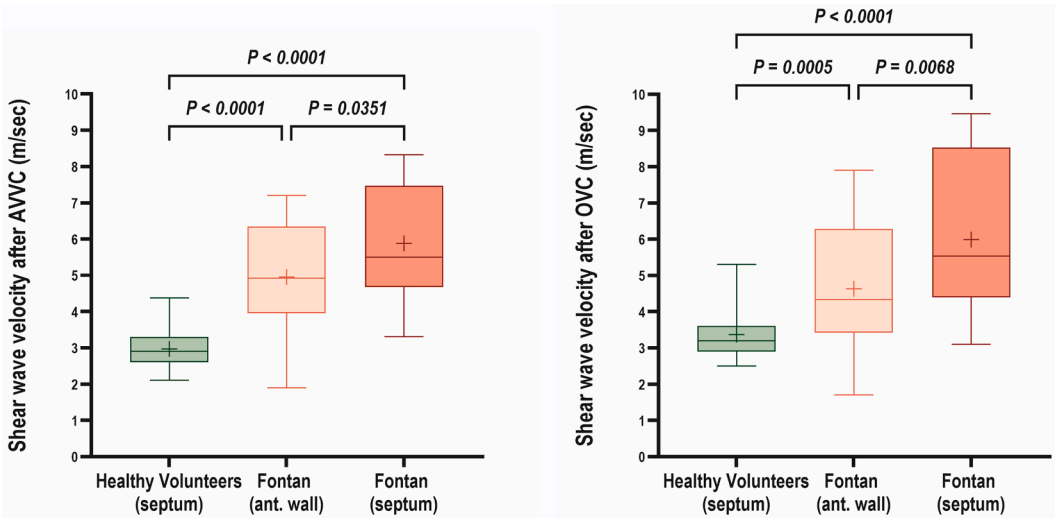
TABLE 2 Clinical Features of the Fontan Cohort Based on Anatomical Variants

	Tricuspid Atresia (n = 12)	DILV (n = 13)	Unbalanced AVSD (n = 5)	HLHS (n = 8)	DIRV (n = 2)	Pulmonary Atresia VSD (n = 4)	Pulmonary Atresia IVS (n = 2)	Ebstein Anomaly (n = 1)
Sex								
Male	7	9	3	6		2	2	1
Female	5	4	2	2	2	2		
Age, y	30 (16-37)	16 (9-28)	10 (8-16)	14 (7-18)	7	25	16	37
Time since Fontan palliation, y	27 (14-34)	12 (5-23)	7 (3-11)	7 (3-11)	4.5	19	13	33
BSA, m^2	1.7 (1.5-1.9)	1.8 (0.9-2.0)	1.2 (0.8-1.8)	1.2 (0.8-1.7)	0.9	1.4	1.4	1.6
BMI, kg/cm^2	21 (18-25)	21 (6-21)	18 (16-36)	17 (15-20)	16	18	21	24
Heart rate, beats/min	78 ± 8	76 ± 11	98 ± 28	72 ± 12	88.5 ± 2.1	81	79	79
Systolic blood pressure, mm Hg	118 ± 12	119 ± 14	107 ± 19	113 ± 8	107 ± 9.9	104	119	127
Diastolic blood pressure, mm Hg	70 ± 6	67 ± 14	71 ± 14	67 ± 15	70 ± 12	67	63	81
Saturation, %	96 (93-98)	95 (92-97)	90 (86-96)	94 (91-98)	90	94	95	92
NYHA functional class	7 (1); 5 (2)	7 (1); 4 (2); 2 (3)	2 (1); 2 (2); 1 (3)	6 (1); 2 (2)	2 (1)	2 (1); 2 (2)	2 (1)	1 (2)
Fontan failure	3	3	3	3	0	1	0	0
Number of patients with SVP measurements	8	10	4	5	-	3	-	-
SVP, mm Hg	19 ± 3	18 ± 5	20 ± 4	18 ± 5	-	16	-	-

Values are mean ± SD or median (IQR); if n < 5 only a mean value is reported.

AVSD = unbalanced atrioventricular canal; DILV = double inlet left ventricle; DIRV = double inlet right ventricle; HLHS = hypoplastic left ventricle; IVS = interventricular septum; SVP = systemic venous pressure; VSD = ventricular septal defect; other abbreviations as in Table 1.

FIGURE 2 **Comparison Between SW Speed Values in Fontan (in the Septum and the Anterior Wall) and in Healthy Volunteers (in the Septum)**



SW speed was significantly higher in Fontan patients both at end-diastole (AVVC) and end-systole (OVC). AVVC = atrioventricular valve closure; OVC = outflow valve closure; other abbreviation as in Figure 1.

Shear wave speed in Fontan patients and age-matched healthy volunteers. In Fontan patients, the average SW speed was 5.3 ± 1.6 m/s after AVVC and 5.1 ± 2.0 m/s after OVC. The mean SW speed in healthy volunteers was 3.0 ± 0.5 m/s after AVVC and 3.4 ± 0.6 m/s after OVC. Values were significantly higher in Fontan patients both after AVVC ($P < 0.001$) and OVC ($P < 0.001$), as shown in Table 1 and Figure 2. Considering Fontan patients alone, SW velocities were slightly slower across the anterior wall compared to the interventricular septum (respectively, 5.0 ± 1.5 m/s vs 5.9 ± 1.7 m/s after AVVC ($P = 0.078$); 4.6 ± 1.7 m/s vs 6.0 ± 2.1 m/s after OVC ($P = 0.029$), although both remained higher when compared to controls ($P < 0.001$). In contrast to healthy volunteers, where SW speed after OVC was higher compared to SW speed after AVVC ($P < 0.0001$), in Fontan patients, there was not significant difference between SW velocity during the cardiac cycle ($P = 0.614$).

Shear wave speed and clinical features. There was no correlation between SW speed and age (r = 0.092; $P = 0.54$ for SW after AVVC r = 0.13; $P = 0.39$ for SW after OVC). The mean SW speed was 5.6 ± 1.7 m/s after AVVC and 5.0 ± 2.3 m/s after OVC in children, 4.7 ± 1.4 m/s after AVVC and 4.9 ± 2.1 m/s after OVC in adolescents, and 5.3 ± 1.6 m/s after AVVC and 5.4 ± 1.7 m/s after OVC in adults. Of interest, the SW speed after OVC was higher in the septum compared to the anterior wall. On average, these patients were also older (Table 1).

In terms of anatomy, SW speed showed no significant difference among patients with a left-dominant ventricle and a right-dominant ventricle, both after AVVC ($P = 0.68$) and OVC ($P = 0.36$). The results appeared similar across different anatomical categories (Table 3).

Patients with Fontan circulatory failure showed higher SW speed after AVVC compared to patients with a well-functioning Fontan circulation (4.9 ± 1.5 m/s vs 6.3 ± 1.4 m/s; $P = 0.008$), as shown in Figure 3.

Correlation of SW velocities with SVP and other echo parameters. SW speed after AVVC, at the end of diastole, showed a correlation with SVP (n = 29; r = 0.55; $P = 0.002$), as demonstrated in Figure 4. Patients with Fontan circulatory failure showed on average higher SVP when compared to well-functioning Fontan (20 ± 4 mm Hg vs 16 ± 2 mm Hg. $P = 0.012$). No other conventional echocardiographic parameter of diastolic function showed a correlation with SVP, as illustrated in Figure 5.

Intraobserver and interobserver variability. Intraobserver variability was excellent (ICC: 0.98; 95% CI: 0.94 to 0.99; $P < 0.0001$). Interobserver variability was very good (ICC: 0.95; 95% CI: 0.8 to 0.99; $P < 0.0001$). Respective Bland-Altman plots are shown in Figure 6.

TABLE 3 Conventional Echo Parameters and SW Speed are Reported for Different Single Ventricles Anatomy Groups

Number of Patients	Tricuspid Atresia (n = 12)	DILV (n = 13)	Unbalanced AVSD (n = 5)	HLHS (n = 8)	DIRV (n = 2)	Pulmonary Atresia VSD (n = 4)	Pulmonary Atresia IVS (n = 2)	Ebstein Anomaly (n = 1)
Ejection fraction/FAC (%)[a]	58 ± 3	54 ± 9	49 ± 12	49 ± 4	48	53	62	64
GLS (%)	−18.9 ± 2.3	−17.2 ± 3.7	−16.3 ± 5	−18.4 ± 2.7	−18.3	−16.3	−15.9	−18.6
E/A	1.5 ± 0.2	1.5 ± 0.5	1.3 ± 0.4	1.6 ± 0.2	1.23	1.64	0.97	1.4
Deceleration time (ms)	177 ± 64	235 ± 94	160 ± 40	183 ± 46	134	245	145	280
E/e'	4.8 (3.9-7.0)	7.1 (4.9-7.8)	7.8 (4.6-9.3)	8.8 (6.3-12.8)	8.7	8.4	6.1	6.1
IVCT (ms)	81 (57-104)	93 (69-116)	120 (81-242)	81 (61-135)	115	87	75	75
IVRT (ms)	82 ± 13	85 ± 18	79 ± 12	86 ± 25	89	75	55	95
Tei-index	0.5 (0.5-0.7)	0.7 (0.5-0.9)	0.8 (0.7-1.4)	0.7 (0.7-0.9)	0.8	0.7	0.5	0.7
S/D	0.8 ± 0.2	0.8 ± 0.3	1 ± 0.4	0.7 ± 0.3	1	0.7	0.8	0.6
SW speed after AVVC (m/s)	5.3 ± 1.8	5.1 ± 1.7	5.3 ± 0.9	5.6 ± 1.1	4.4 ± 0.1	5.5	7.0	6.3
SW speed after OVC (m/s)	4.9 ± 1.4	5.1 ± 2	5.1 ± 1.4	4.4 ± 1.8	3.8 ± 0.7	7.2	6.3	4.4

Values are mean ± SD or median (IQR); if n < 5 only a mean value is reported. [a]We used LV ejection fraction by the biplane Simpson method for morphologically left univentricular hearts and fractional area change for morphologically right ventricles.

Abbreviations as in Tables 1 and 2.

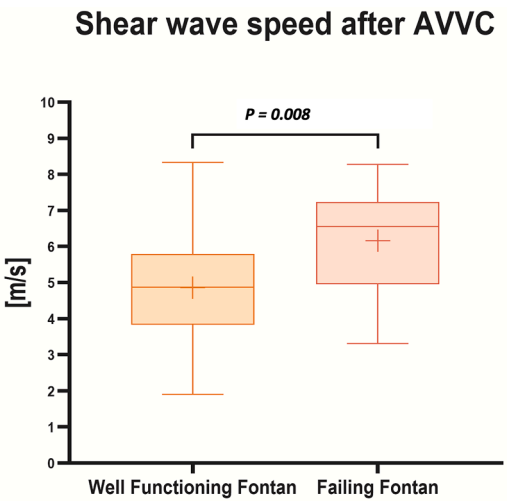
DISCUSSION

To the best of our knowledge, this is the first study to characterize the behavior of naturally occurring SWs in patients with a Fontan circulation. Our work provides novel insights into the feasibility and clinical relevance of natural SW velocity measurements in this complex congenital heart disease group. Importantly, we demonstrate for the first time a significant, albeit moderate, correlation between SW velocities—particularly after AVVC—and SVP, suggesting that natural SW speed may serve as a promising noninvasive marker of hemodynamic status in Fontan patients (Central Illustration).

To date, data on SWE in children and adults palliated with a Fontan circulation remain limited. A recent study by Salaets et al[33] assessed ventricular stiffness using induced SWs in 24 pediatric Fontan patients, showing significantly increased end-diastolic stiffness compared to controls, without statistical differences between left- and right-dominant ventricles. Similarly, our findings revealed significantly higher SW velocities post-AVVC and OVC in Fontan patients (Figure 2). This likely reflects ventricular remodeling and reduced compliance due to chronic preload deprivation, which results in a stiffer ventricle.[2] Interestingly, the observed velocities align with those reported in multisystem inflammatory syndrome in children patients, where myocardial inflammation and edema contribute to increased stiffness.[34]

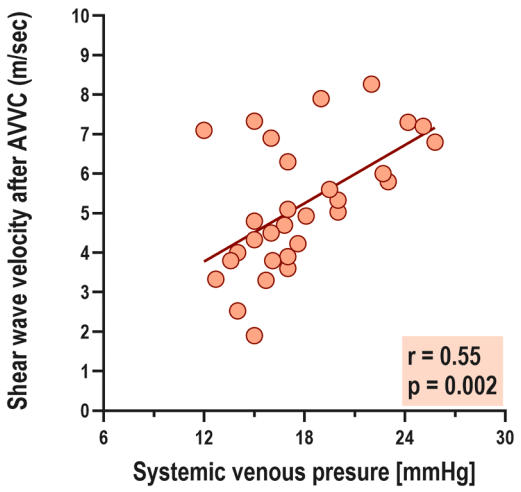
Although feasible in the majority of cases, the need to measure in the anterior wall in a subgroup of patients is challenging. Further investigation in wave physics in single ventricle physiology is needed and is a barrier to easily extrapolate findings from other studies. Pragmatically, we focused our analysis on the wave that was most consistently aligned with AVVC, as it corresponds temporally to the naturally occurring wave observed after MVC in biventricular hearts. Nevertheless, the heterogeneous atrioventricular valve anatomy in the Fontan population may

FIGURE 3 Comparison Between SW Speed Values in Well-Functioning Fontan and in Patients With Fontan Circulatory Failure



Patients with Fontan circulatory failure showed significantly increased SW speed after AVVC. Abbreviations as in Figures 1 and 2.

FIGURE 4 SW Velocities and Systemic Venous Pressure



SW velocities after AVVC correlated significantly with SVP ($P = 0.002$). Abbreviations as in Figures 1 and 2.

give rise to waves with distinct physical characteristics, potentially offering additional and highly informative physiological insights. Together with the presence of multiple waves observed around the time of valve closure, future studies should further explore their origins, physical properties, and clinical relevance.

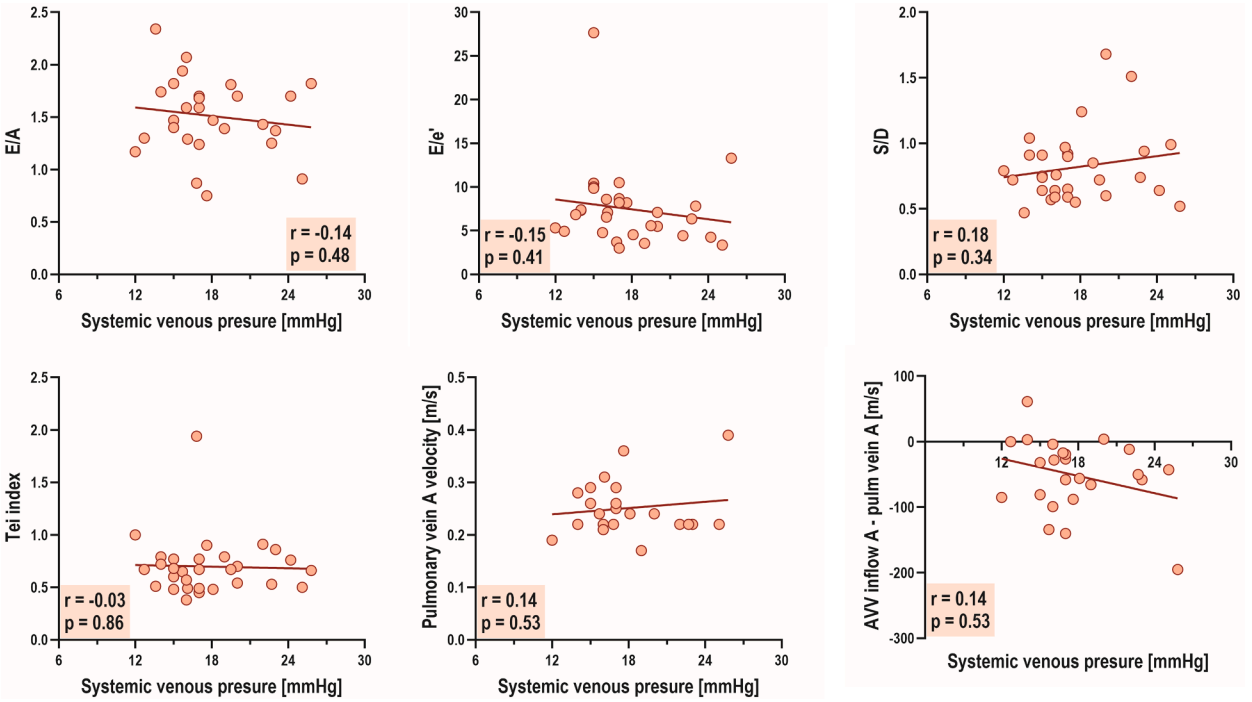
Previous research has shown that SW speed is age-dependent in healthy individuals due to growth-related changes in diastolic function.[20,23] In contrast to Salaets et al,[33] we did not observe an age-related increase in SW velocities in Fontan patients. One could speculate that this could be related to early remodeling variability in surgical pathway between patients or survivor bias for adult Fontan patients. However, the fact that children were more likely to be included at the time of cardiac catheterization, although adult patients were mainly recruited in the outpatient clinic, will have introduced selection bias. Finally, the observation of higher SW velocities measured in the septum, in a group of patients that was on average older (hinting towards an age relation), indicates the complexity of the analysis. A longitudinal analysis of individual patients is required to confirm or refute age-dependency of these parameters.

An animal study by Bezy et al[22] suggests that increased SW speed after AVVC may result from changes in both MS and/or loading conditions. Different studies report a profibrotic environment in Fontan patients whereas invasive exercise hemodynamic confirms marked abnormalities in ventricular compliance.[35] Filling pressures and tissue properties appear tightly linked in this group since T1 signal on cardiac MRI appears higher in patients with a single ventricle compared to other congenital heart disease and the extension of fibrosis correlates to increased end-diastolic pressures.[36] Although right-dominant ventricles have been reported as more fibrosis-prone,[5] our findings, in line with Salaets et al,[33] did not show a significant difference in stiffness between right and left ventricles. This may reflect the younger age of our right-dominant subgroup (Table 1). However, more likely, the limited size of the anatomical subgroups may have reduced the statistical power to detect such differences.

Filling and SVPs are critical prognostic indicators in Fontan physiology.[12,26] However, traditional echocardiographic parameters of diastolic function are unreliable in this group. Although Cordina et al[28] showed that the S/D ratio predicts elevated end-diastolic pressure in adult Fontan patients, this was not reproducible in pediatric populations or in our study. In our study group, there was a moderate correlation between SW velocity after AVVC and SVP (Figure 4). SVP is a compound measure, reflecting ventricular and atrial stiffness, systolic ventricular function, atrioventricular valve regurgitation and pulmonary vascular resistance. In adult Fontan patients, SVP is closely linked to pulmonary capillary wedge pressure.[28] Our findings indicate the potential application of SW speed after AVVC as a noninvasive marker of hemodynamic status. In addition, we observed significantly higher SW velocities after AVVC in patients with Fontan circulatory failure (Figure 3) further confirming its value in assessing Fontan hemodynamics. Interestingly, none of the conventional diastolic parameters showed any correlation with SVP (Figure 5).

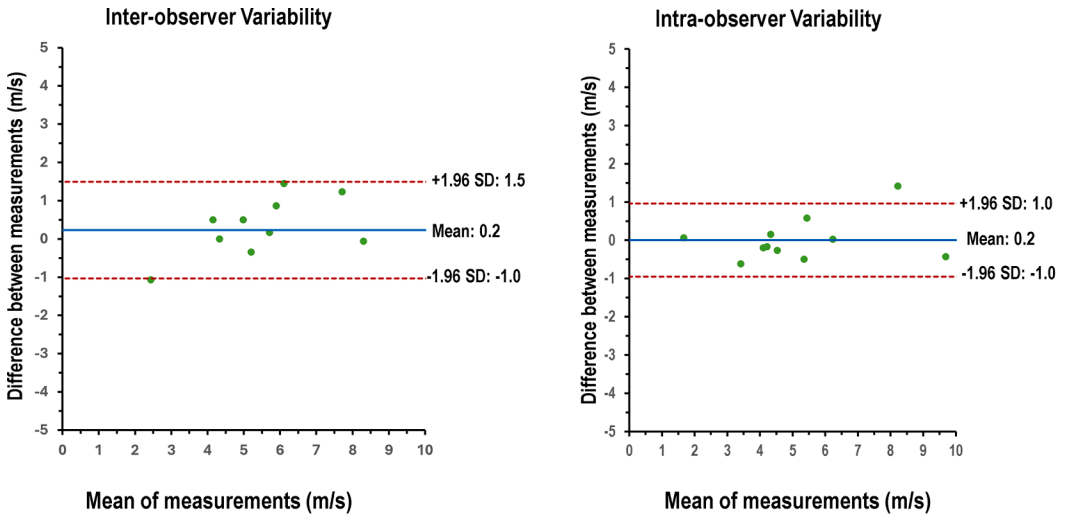
However, a more precise description of loading status and fibrotic remodeling to directly relate SW velocities to filling pressures are needed to disentangle the relative contributions from altered loading conditions and fibrotic remodeling to increased SW velocities observed in the current study. In the current cross-sectional design, the increased SW velocities in univentricular hearts should be interpreted as an integrated marker of both myocardial properties and hemodynamic status. Longitudinal studies to assess changes over time may inform us whether absolute thresholds (to identify those with worse hemodynamics) or changes over time (to identify clinical worsening) are more useful in this patient population.

FIGURE 5 Conventional Echo Parameters of Diastolic Function and Systemic Venous Pressure



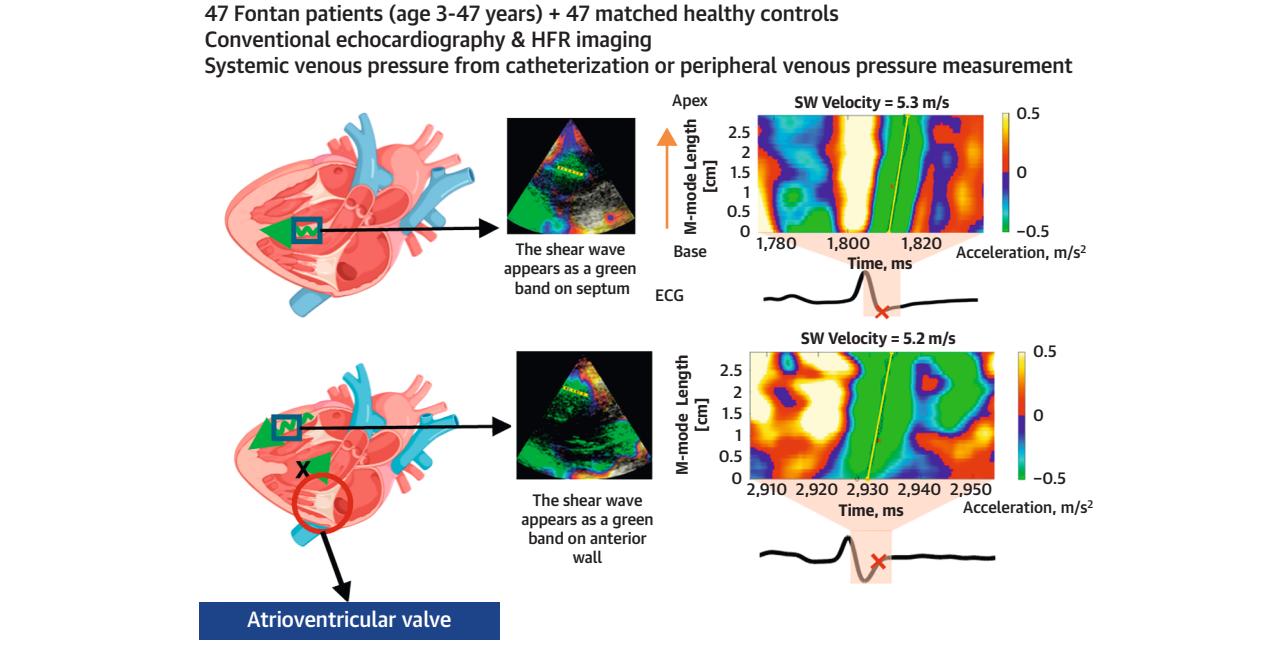
None of the conventional parameters of diastolic function showed any correlation with SVP ($P > 0.05$). E/A = early to-late inflow velocity ratio; E/e' = inflow to relaxation velocity ratio; S/D = systolic to diastolic duration ratio; other abbreviation as in Figure 2.

FIGURE 6 Interobserver and Intraobserver Variability



The Bland-Altman plot on the left shows a good agreement between SW speed measurements from 2 different observers (I.C. and A.Y.). The Bland-Altman plot on the right shows a good agreement between repeated SW speed measurements from the same observer (A.Y.).

CENTRAL ILLUSTRATION **Natural SWE Imaging in Patients With a Fontan Circulation**



Cattapan I, et al. JACC Adv. 2026;5(3):102608.

ECG = electrocardiogram; HFR = high frame rate; SW = shear wave; SWE = shear wave elastography.

Notably, SW velocities captured after AVVC are measured during the isovolumic contraction phase and have been shown to be closely associated with end-diastolic filling pressures and MS in biventricular hearts.[16,22] Given their timing within the isovolumic contraction phase, natural SW velocities after AVVC in Fontan patients reflect operational MS[21] and filling pressures at that specific time point, rather than being direct measures of diastolic function.

Lastly, we also noticed elevated SW speed after OVC (end-systole) in Fontan patients compared to controls. These values were on average slightly lower than end-diastolic velocities and did not show significant intrapatient difference. This pattern resembles findings in cardiac amyloidosis, suggesting a potential contribution of fibrosis to systolic stiffness.[20] Interestingly, SW velocities after OVC (or AVVC) did not correlate with ejection fraction or global longitudinal strain, indicating they may reflect tissue properties not captured by conventional metrics. Alternatively, the lack of correlation may relate to the limited validation of ejection fraction and strain in the Fontan population, where complex anatomy and marked heterogeneity may render these indices suboptimal surrogates of systolic contractility, thereby explaining the absence of an association with SW velocities.

STUDY LIMITATIONS. First, the population of patients with single ventricle physiology who have undergone Fontan palliation remains relatively small, limiting the ability to conduct studies with large sample sizes.

Second, the marked heterogeneity within the Fontan cohort—stemming from variations in underlying cardiac anatomy and the type of surgical palliation performed—poses significant challenges for the measurement and interpretation of SW velocities across anatomies and subgroups in a study with a cross-sectional design.

Third, SWs are typically assessed in the interventricular septum. Sometimes, the lack of an intact septum in this population increases the heterogeneity in SW tracking and analysis, necessitating a cautious interpretation of the velocities measured. Indeed, geometric differences between the assessed regions—namely the thick septal wall vs the thinner anterior wall—may influence SW propagation, as demonstrated by Malik et al.[37] Nevertheless, the relatively thick anterior free wall in single-ventricle patients permits feasible SW tracking comparable to septal measurements. The consistently lower SW velocities observed in the anterior wall compared with the septal region likely reflect the combined effects of geometric differences and MS variations and should therefore be interpreted with caution.

In addition, the wide range of phenotypic presentations may influence SW behavior and velocity measurements. For instance, the presence of a ventricular septal defect may alter the typical propagation pattern of SWs, potentially introducing longitudinal wave components and resulting in an overestimation of velocity. Alternatively, SWs may propagate around the septal defect and reach the anterior wall in an apex-to-base direction, which could explain our observation of waves propagating in the opposite direction. However, this represents a limitation of 2-dimensional imaging, as the true origin of reversely propagating waves cannot be accurately determined. Three-dimensional SWE may overcome this limitation by enabling more accurate identification of wave origins.

Furthermore, it remains unclear whether valvular abnormalities such as stenosis or regurgitation significantly affect SW propagation speed.

CONCLUSIONS

To the best of our knowledge, this is the first study to demonstrate the feasibility of natural SWE in patients with single ventricle physiology following Fontan palliation. On average, SW velocity was higher in Fontan patients than in healthy controls, possibly reflecting increased MS. We found that end-diastolic SW velocity correlated with SVP. This novel observation suggests that SWE may provide unique insights into the hemodynamic status of this complex physiology. Furthermore, patients with clinical signs of Fontan failure—regardless of the underlying etiology—demonstrated increased end-diastolic SW speeds, supporting the hypothesis that ventricular stiffness may play a central role in Fontan circulatory failure.

FUNDING SUPPORT AND AUTHOR DISCLOSURES

Dr Van De Bruaene is supported by a Single Ventricle Research Grant from Additional Ventures (1012382). Dr Youssef is supported by a scholarship from the Egyptian ministry of higher education, The Belgian Fund for Cardiac Surgery, and The Frans Van De Werf fund. Dr D'hooge performs research under contracts for GE Vingmed Healthcare and Cardiac. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

ADDRESS FOR CORRESPONDENCE: Dr Alexander Van De Bruaene, Department of Cardiovascular Sciences, KU Leuven, Division of Structural and Congenital Cardiology, UZ Leuven Herestraat 49, 3000 Leuven, Belgium. E-mail: alexander.vandebruaene@uzleuven.be.

PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: We assessed the feasibility and behavior of natural SWE in pediatric and adult patients after Fontan palliation. SW velocities were significantly higher in patients with Fontan circulatory failure compared with well-functioning Fontan patients and showed a positive association with SVP, possibly reflecting increased MS and altered hemodynamic status in this complex population. These findings suggest that SW imaging has the potential to serve as a feasible, noninvasive tool for monitoring patients after Fontan palliation.

TRANSLATIONAL OUTLOOK: Progressive ventricular stiffening and diastolic dysfunction are central mechanisms underlying Fontan circulatory failure. However, evaluating these processes in the heterogeneous population of children and adults with Fontan physiology remains challenging because of variable hemodynamics and complex anatomy. Direct assessment of MS and hemodynamic status currently requires invasive measurement of the end-diastolic pressure-volume relationship. SWE may emerge as a practical, easy-to-use tool to facilitate noninvasive assessment of MS in both experimental and clinical studies.

REFERENCES

1. Chowdhury UK, George N, Sankhyan LK, et al. Fontan failure: phenotypes, evaluation, management and future directions. *Cardiol Young*. 2022;32:1554-1563. https://doi.org/10.1017/s1047951122001433

2. Gewillig M, Goldberg DJ. Failure of the fontan circulation. *Heart Fail Clin*. 2014;10:105-116. https://doi.org/10.1016/j.hfc.2013.09.010

3. Van De Bruaene A, La Gerche A, Claessen G, et al. Sildenafil improves exercise hemodynamics in Fontan patients. *Circ Cardiovasc Imaging*. 2014;7:265-273. https://doi.org/10.1161/CIRCIMAGING.113.001243

4. Gewillig M, Brown SC, van de Bruaene A, et al. Providing a framework of principles for conceptualising the Fontan circulation. *Acta Paediatr*. 2020;109:651-658. https://doi.org/10.1111/apa.15098

5. Kato A, Riesenkampff E, Yim D, et al. Pediatric Fontan patients are at risk for myocardial fibrotic remodeling and dysfunction. *Int J Cardiol*. 2017;240:172-177. https://doi.org/10.1016/j.ijcard.2017.04.073

6. Ho SY, Jackson M, Kilpatrick L, et al. Fibrous matrix of ventricular myocardium in tricuspid atresia compared with normal heart. A quantitative analysis. *Circulation*. 1996;94:1642-1646. https://doi.org/10.1161/01.CIR.94.7.1642

7. Padalino MA, Castellani C, Toffoli S, et al. Pathological changes and myocardial remodelling related to the mode of shunting following surgical palliation for hypoplastic left heart syndrome. *Cardiol Young*. 2008;18:415-422. https://doi.org/10.1017/S1047951108002461

8. Van De Bruaene A, Claessen G, Salaets T, et al. Late fontan circulatory failure. What drives systemic venous congestion and low cardiac output in adult Fontan patients? *Front Cardiovasc Med*. 2022;9:825472. https://doi.org/10.3389/fcvm.2022.825472

9. Budts W, Ravekes WJ, Danford DA, et al. Diastolic heart failure in patients with the Fontan circulation: a review. *JAMA Cardiol*. 2020;5:590-597. https://doi.org/10.1001/jamacardio.2019.5459

10. Gewillig M, Cools B, Van De Bruaene A. Pulmonary vascular reserve in Fontan patients: looking upstream for the true heart of the matter. *J Am Coll Cardiol*. 2020;76:2764-2767. https://doi.org/10.1016/j.jacc.2020.10.006

11. Howell M, Anderson WE, Alegria J, et al. Body mass index and age are associated with ventricular end-diastolic pressure in adults with a Fontan circulation. *Cardiol Young*. 2022;32(8):1296-1301. https://doi.org/10.1017/S1047951121004091

12. Miranda WR, Hagler DJ, Taggart NW, et al. Elevated ventricular filling pressures and long-term survival in adults Post-Fontan. *Catheter Cardiovasc Interv*. 2020;95:803-809. https://doi.org/10.1002/ccd.28340

13. Margossian R, Sleeper LA, Pearson GD, et al. Assessment of diastolic function in single-ventricle patients after the Fontan procedure. *J Am Soc Echocardiogr*. 2016;29:1066-1073. https://doi.org/10.1016/J.ECHO.2016.07.016

14. Menon SC, Gray R, Tani LY. Evaluation of ventricular filling pressures and ventricular function by Doppler echocardiography in patients with functional single ventricle: correlation with simultaneous cardiac catheterization. *J Am Soc Echocardiogr*. 2011;24:1220-1225. https://doi.org/10.1016/J.ECHO.2011.08.011

15. Petrescu A, Cvijic M, Wouters L, et al. Ultrasound shear wave elastography for detection of myocardial fibrosis. *Eur Heart J Cardiovasc Imaging*. 2025;26(9):1537-1545. https://doi.org/10.1093/ehjci/jeaf200

16. Werner AE, Bézy S, Wouters L, et al. Prediction of left ventricular filling pressures using natural shear waves. *JACC Cardiovasc Imaging*. 2025;18(10):1071-1089. https://doi.org/10.1016/j.jcmg.2025.04.009

17. Sigrist RMS, Liau J, el Kaffas A, et al. Ultrasound elastography: review of techniques and clinical applications. *Theranostics*. 2017;7:1303-1329. https://doi.org/10.7150/thno.18650

18. Caenen A, Pernot M, Nightingale KR, et al. Assessing cardiac stiffness using ultrasound shear wave elastography. *Phys Med Biol*. 2022;67. https://doi.org/10.1088/1361-6560/ac404d

19. Cikes M, Tong L, Sutherland GR, et al. Ultrafast cardiac ultrasound imaging technical principles, applications, and clinical benefits. *JACC Cardiovasc Imaging*. 2014;7:812-823.

20. Petrescu A, Santos P, Orlowska M, et al. Velocities of naturally occurring myocardial shear waves increase with age and in cardiac amyloidosis. *JACC Cardiovasc Imaging*. 2019;12:2389-2398. https://doi.org/10.1016/j.jcmg.2018.11.029

21. Villalobos Lizardi JC, Baranger J, Nguyen MB, et al. A guide for assessment of myocardial stiffness in health and disease. *Nature Cardiovasc Res*. 2022;1:8-22. https://doi.org/10.1038/s44161-021-00007-3

22. Bézy S, Duchenne J, Orlowska M, et al. Impact of loading and myocardial mechanical properties on natural shear waves. *JACC Cardiovasc Imaging*. 2022;15:2023-2034. https://doi.org/10.1016/j.jcmg.2022.07.011

23. Youssef AS, Petrescu A, Salaets T, et al. Evolution of natural myocardial shear wave behavior in young hearts: determinant factors and reproducibility analysis. *J Am Soc Echocardiogr*. 2024;37:1051-1061. https://doi.org/10.1016/j.echo.2024.07.004

24. Miranda WR, Borlaug BA, Hagler DJ, et al. Haemodynamic profiles in adult Fontan patients: associated haemodynamics and prognosis. *Eur J Heart Fail*. 2019;21:803-809. https://doi.org/10.1002/ejhf.1365

25. Miranda WR, Egbe AC, Van De Bruaene A, et al. Peripheral venous pressure accurately reflects invasively measured resting and exercise fontan pressures. *Am J Cardiol*. 2024;215:62-64. https://doi.org/10.1016/j.amjcard.2024.01.014

26. Cieplucha A, Van Belle H, Miranda WR, et al. Semi-invasive pressure-flow plots obtained using exercise echocardiography relate to clinical status and exercise capacity in patients with a Fontan circulation. *J Am Soc Echocardiogr*. 2025;38(9):843-854. https://doi.org/10.1016/j.echo.2025.05.007

27. Ginde S, Goot BH, Frommelt PC. Imaging adult patients with Fontan circulation. *Curr Opin Cardiol*. 2017;32:521-528. https://doi.org/10.1097/HCO.0000000000000422

28. Cordina R, Ministeri M, Babu-Narayan SV, et al. Evaluation of the relationship between ventricular end-diastolic pressure and echocardiographic measures of diastolic function in adults with a Fontan circulation. *Int J Cardiol*. 2018;259:71-75. https://doi.org/10.1016/j.ijcard.2018.02.045

29. Santos P, Petrescu AM, Pedrosa JP, et al. Natural shear wave imaging in the human heart: normal values, feasibility, and reproducibility. *IEEE Trans Ultrason Ferroelectr Freq Control*. 2019;66:442-452. https://doi.org/10.1109/TUFFC.2018.2881493

30. Cvijic M, Bézy S, Petrescu A, et al. Interplay of cardiac remodelling and myocardial stiffness in hypertensive heart disease: a shear wave imaging study using high-frame rate echocardiography. *Eur Heart J Cardiovasc Imaging*. 2020;21:664-672. https://doi.org/10.1093/EHJCI/JEZ205

31. Papadacci C, Finel V, Villemain O, et al. 4D ultrafast ultrasound imaging of naturally occurring shear waves in the human heart 2019. *IEEE Trans Med Imaging*. 2020;39:4436-4444. https://doi.org/10.1109/TMI.2020.3020147i

32. Caenen A, Papangelopoulou K, Wouters L, et al. 3D high-frame-rate imaging of natural shear waves in the parasternal view of the heart. *IEEE Open J Ultrasonics, Ferroelectrics, and Frequency Control*. 2025;5:1-5. https://doi.org/10.1109/ojuffc.2025.3538819

33. Salaets T, Venet M, Malik A, et al. Diastolic myocardial stiffness assessed by shear wave elastography in children with a Fontan circulation. *J Am Soc Echocardiogr*. 2024;37(11):1116-1118. https://doi.org/10.1016/j.echo.2024.07.010

34. Youssef AS, Salaets T, Bézy S, et al. Shear-wave elastography reflects myocardial stiffness changes in pediatric inflammatory syndrome post COVID-19. *JACC Cardiovasc Imaging*. 2024;17(2):214-216. https://doi.org/10.1016/j.jcmg.2023.08.003

35. Alsaied T, Moore RA, Lang SM, et al. Myocardial fibrosis, diastolic dysfunction and elevated liver stiffness in the Fontan circulation. *Open Heart*. 2020;7(2):e001434. https://doi.org/10.1136/openhrt-2020-001434

36. Beigh MVR, Pajunen KBE, Pagano JJ, et al. T1 mapping of the myocardium and liver in the single ventricle population. *Pediatr Radiol*. 2023;53:1092-1099. https://doi.org/10.1007/s00247-022-05560-y

37. Malik A, Baranger J, Nguyen MB, et al. Impact of ventricular geometric characteristics on myocardial stiffness assessment using shear-wave velocity in healthy children and young adults. *J Am Soc Echocardiogr*. 2023;36:849-857. https://doi.org/10.1016/j.echo.2023.02.012

KEY WORDS **diastolic function, Fontan circulation, high frame rate echocardiography, shear wave elastography**