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Right ventricular function in pulmonary arterial hypertension: The influence of longitudinal strain on hemodynamic measurements

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Abstract

Right ventricular longitudinal strain (RVLS) is a new parameter of right ventricular (RV) function. The aim of this study was to evaluate RVLS to detect subtle RV dysfunction and its correlation with hemodynamic measurements in patients with pulmonary arterial hypertension (PAH). Thirty-five PAH patients were enrolled in this study. Right heart catheterization and echocardiography were performed in all patients. RV free wall strain (RV FWS) and RV global longitudinal strain (RV GLS) were measured using 2D speckle-tracking echocardiography (STE). The correlations between RVLS and invasive hemodynamics were analyzed. Of the 35 subjects, 85.7% were classified as WHO functional class I/II, with a mean age of 34.7 ± 12.9 years. RV systolic function conventional parameters remained in the normal range despite a high mean RV systolic pressure (RVSP) of 87.2 ± 42.4 mmHg. However, mean RV GLS and RV FWS exhibited lower values (-17.0 ± 5.8% and -18.6 ± 6.2%, respectively). RV GLS and RV FWS showed significant correlation with mean pulmonary arterial pressure (mPAP) and PVR (r=0.493, P = 0.003, r = 0.518, P = 0.008, r = 0.575, P = < 0.05, r = 0.485, P = 0.003, respectively). Conclusions: Despite normal conventional right ventricular (RV) function assessment, RV strain in this study showed decreased values. Right ventricular strain also demonstrated a significant correlation with invasively assessed mean pulmonary arterial pressure (mPAP) and pulmonary vascular resistance (PVR) in patients with pulmonary arterial hypertension (PAH). This correlation may be useful in clinical practice for assessing the impact of pre-capillary pulmonary hypertension (PH) on early myocardial right heart dysfunction.

Keywords: 2D speckle-tracking echocardiography, Hemodynamic, Pulmonary arterial hypertension, Right ventricular strain.

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Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
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1. Introduction

Pulmonary arterial hypertension (PAH), defined as World Heart Organization (WHO) Group 1 Pulmonary Hypertension (PH), is a progressive, fatal condition of the pulmonary arterioles, resulting in elevated resistance and pressure in the pulmonary arteries and right ventricular (RV) overload [1]. Despite advancements in treatment options, causes of death remain related to right ventricular failure. Development of RV dysfunction in patients with PAH is associated with a poor prognosis, irrespective of the underlying clinical condition. As a result, the assessment of RV function has become more important in risk stratification and in the clinical management of PAH patients [2, 3].

Right ventricular systolic dysfunction is an important prognostic factor in PAH patients. However, RV assessment can be challenging. Right heart catheterization can provide important pressure- and flow-derived parameters in the diagnosis and management of PAH patients, but this method is invasive and impractical [2]. Cardiac magnetic resonance (CMR) is accepted as the best modality to evaluate RV function because it delineates endocardial contours and accounts for the RV outflow tract. This modality can provide morphological and functional information about the RV. However, echocardiography is still preferred for routine clinical practice because it is more widely available and requires less time for imaging [1-4]. American Society of Echocardiography (ASE) recommendations provide a list of echocardiographic parameters for assessing RV function [5, 6]. Nevertheless, evaluating the function of the RV by echocardiography is challenging due to the complex anatomy of the RV, narrow acoustic windows, and geometric assumptions in volumetric calculations, which compromise accurate assessment of regional or subtle myocardial dysfunction in the early stages of PAH. Conventional indices such as tricuspid annular plane systolic excursion (TAPSE), right ventricular fractional area change (RVFAC), right ventricular tissue Doppler imaging systolic velocity (RV TDI S′ velocity), and the RV Tei Index suffer from major limitations because they are angle-dependent and are assessed only in a one-dimensional format. These parameters are also limited by the three-dimensional geometry and the load dependence of the right ventricle [5, 6]. Three-dimensional right ventricular ejection fraction (RV 3D EF) is a new metric that has been found to correlate strongly with CMR. The RV 3D EF is capable of evaluating two components of RV systole (longitudinal, radial) and is not restricted by the geometric assumptions required by standard echocardiographic parameters. It offers a comprehensive reflection of RV systolic function, but it is an indirect reflection of systolic work in the sense that it is load-dependent and depicts the relationship between the systolic phase and the load. There are several challenges, such as the requirement of dedicated 3D analysis, data acquisition, analysis expertise, time-consuming post-processing, and high variations also observed from manufacturers [6-8].

More recently, 2D speckle-tracking echocardiography (STE) has been proven to be superior in the assessment of myocardial strain and provides more sensitive measurements for early detection of myocardial deformation. Two-dimensional STE has been described as a useful complementary technique for measuring RV function. A number of studies have shown the role of strain parameters in prognosis because of early/subclinical detection of RV dysfunction [9-13]. Normative reference values for RV 2D STE are also available in normal populations [14]. Nevertheless, only a few studies described the association between RV mechanics and invasively measured parameters in patients with PH. Some studies were conducted in all types of PH patients with decreased values of RV systolic function. Thus, this study aimed to evaluate the correlation of right ventricular longitudinal strain using 2D STE and hemodynamic parameters in PAH patients with subtle RV dysfunction.

2. Materials and Methods

2.1. Study Sample

A single-center prospective study was conducted involving 35 adult patients (>18 years old) with World Health Organization (WHO) group 1 pulmonary arterial hypertension (PAH), confirmed through right heart catheterization (RHC) between November 2023 and June 2024. Hemodynamic assessment was performed using both left and right heart catheterization, along with comprehensive transthoracic echocardiography (TTE) examinations in all PAH patients. All participants met the current diagnostic criteria and attended regular outpatient follow-ups at this institution. Patients with left ventricular (LV) systolic dysfunction, coronary artery disease, cardiomyopathy, significant left valvular disease (moderate to severe aortic or mitral stenosis or regurgitation), chronic thromboembolic disease, pulmonary parenchymal diseases, and/or poor image quality were excluded. Clinical data such as symptoms, signs, levels of N-terminal pro B-type natriuretic peptide (NT-proBNP), and creatinine values were recorded. All patients provided written informed consent to participate in the study, which was approved by our Institute's Research Ethics Committee (ethical approval number DP.04.03/D.XVI.XI/558/2023), obtained on October 20th, 2023.

2.2. Conventional Right Ventricular Echocardiographic Examination

A comprehensive two-dimensional (2D) analysis and Doppler echocardiography were performed using a Vivid E95 (GE Vingmed, Horton, Norway; 4Vc-D 3D/4D phased array transducer) ultrasound system. All investigators in the echocardiography laboratory were blinded to invasively derived data. Routine left and right heart echocardiographic parameters were performed according to the recommendations of the American Society of Echocardiography (ASE) [5]. The conventional RV function parameters included TAPSE, RV TDI S′ velocity, and RVFAC. We also measured the RV 3D EF (Figure 1A). TAPSE was recorded with M-mode echocardiography parallel to the lateral RV wall and across the tricuspid annular plane, and it was quantified as the systolic excursion of the RV annulus in the longitudinal plane. RVFAC was calculated from the apical four-chamber view, and it is defined as follows: (RV end-diastolic area - RV end-systolic area) / RV end-diastolic area × 100%. Pulmonary arterial systolic pressure (PASP) was calculated by summing the peak gradient of tricuspid regurgitation (TR) and the estimated right atrial pressure (RAP). RAP estimations were scored as 3, 8, or 15 mmHg based on the inferior vena cava (IVC) diameter and respiratory variation [5, 6].

2.3. Two-Dimensional Speckle-Tracking Echocardiography

Two-dimensional speckle-tracking echocardiography (2D-STE)-derived longitudinal right ventricular (RV) strain parameters (RVLS) were obtained from the RV-focused apical four-chamber view, with an attempt to visualize the entire RV length and to prevent foreshortening of the RV apex (Figure 1B). The frame rate varied between 60 and 80 frames per second. After acquiring an RV-focused view with good visualization of the RV wall, the GE Echopac software was used, and the selected AutoStrain RV mode was chosen to begin the analysis. In cases of extremely dilated trabeculated RV, endocardial contour, end-diastolic start, and end-diastolic end markers can be manually adjusted. In the analysis, the global measurement of the right ventricle free wall strain (RV FWS) and RV four-chamber global longitudinal strain (RV GLS) are displayed (Figure 1B). The peak systolic longitudinal strain has a negative percentage value, indicating tissue contraction/shortening. Negative strain values indicate tissue shortening, and a smaller value (i.e., a higher absolute value) indicates better RV systolic function [14]. Longitudinal strain measurements for each patient were performed offline in a blinded manner by two independent observers. Each observer conducted two independent measurements of regional and global RV strain values using Echopac software on the same echocardiographic images in all patients.

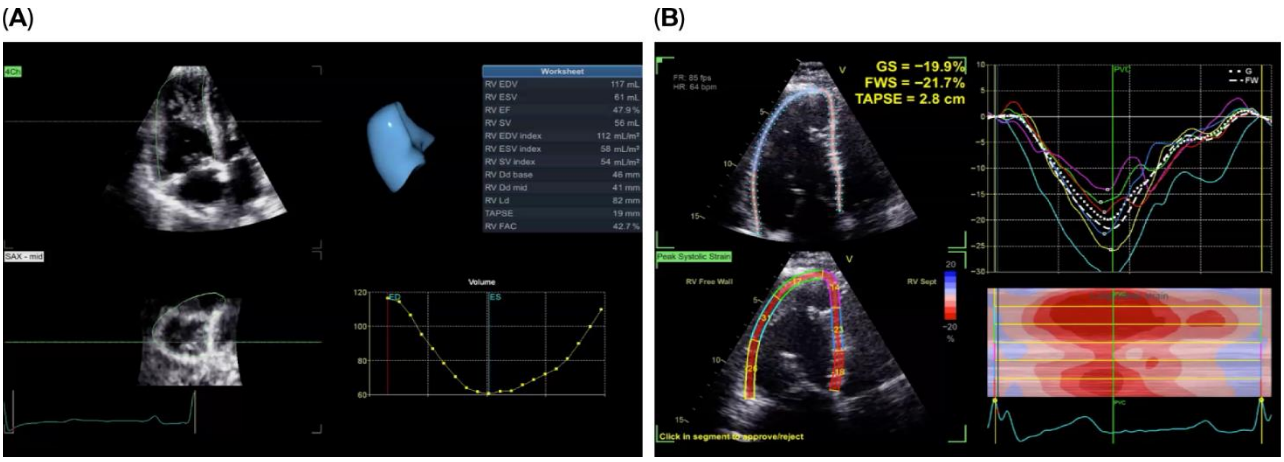

Figure 1. A).
The image shows a focused view of the apical four-chamber RV for the estimation of the 3D RV ejection fraction (**B**) The image illustrates the calculation of RV strain values in the analysis process. The strain values are displayed as the right ventricle four-chamber global longitudinal strain (RV4GS) and right ventricle free wall longitudinal strain (RVFWSL).

2.4. Right Heart Catheterization

All patients underwent right heart catheterization. Briefly, arterial and venous access were established by inserting a needle into the femoral artery and vein. Then, a 6-Fr fluid-filled pigtail catheter was placed in the LV for measurement of LV end-diastolic pressure (LVEDP). For the measurement of right heart pressure, mean pulmonary artery pressure (mPAP), and pulmonary capillary wedge pressure (PCWP), a Corodyn P1 right heart catheter was used. The exact position of the catheter was determined by changes in the pressure waveform and fluoroscopy. The cardiac index (CI), systemic vascular resistance (SVR), and pulmonary vascular resistance (PVR) were calculated. All patients were hemodynamically stable at the time of examination. Cardiac output was determined using the Fick method. PVR was calculated using the formula (mPAP - PCWP) / cardiac output and reported in Wood units [15].

2.5. Data Analysis

Statistical analysis was performed using SPSS 24.0 (IBM Corporation, Armonk, NY, USA). Descriptive statistics were reported as mean values ± standard deviation or percentages of patients. Categorical variables between the two groups were compared using Pearson's chi-squared test. Continuous variables between the two groups were compared using independent sample *t*-tests for normally distributed data and the Mann–Whitney U test for non-normally distributed data. The Pearson correlation coefficients for normally distributed data and Spearman correlation coefficients for non-normally distributed data were used to evaluate the relationship between echocardiographic parameters and hemodynamic parameters in this study. A two-tailed p-value was considered statistically significant of <0.05 was considered statistically significant. The strength of the association between the variables was indicated by a Pearson correlation coefficient (r) less than 0.40 (weak correlation), between 0.40 and 0.70 (moderate correlation), or greater than 0.70 (strong correlation) [16].

3. Results

3.1. Study Sample

A total of 35 patients (30 females, mean age: 34.7 ± 12.9 years) with WHO group I PAH (31 patients with congenital heart disease and 4 patients with idiopathic PH) were included in this study. The baseline characteristics of the study sample are summarized in Table 1, and echocardiographic variables are presented in Table 2. The majority of patients were classified as WHO functional class I/II (85.7%). All patients received phosphodiesterase type 5 inhibitors (PDE-5I) at the time of inclusion in this study. Fourteen patients (40%) were taking a single vasodilator medication, and 21 (60%) patients were taking a combination of vasodilators (PDE-5I and prostacyclin analogues). In terms of laboratory findings, an increase in NT-proBNP levels was observed in this study. All patients underwent right heart catheterization (RHC) prior to diagnosis and treatment. The mean pulmonary artery (PA) pressure was 46.5 ± 20.5 mmHg, the mean right atrial (RA) pressure was 11.5 ± 3.9 mmHg, and the pulmonary vascular resistance was 10.4 ± 1.3 Wood units (WU).

Table 1.
Baseline characteristics of the PAH study sample.

Characteristics	Overall (*n* = 35)
Clinical	
Age, years, mean ± SD	34.7 ± 12.9
Female gender, *n* (%)	30 (85.7)
Body mass index (kg/m^2)	23.2 ± 7.7
WHO class I/II, *n* (%)	30 (85.7)
WHO class III/IV, *n* (%)	5 (14.3)
Hypertension, *n* (%)	1 (2.9)
Diabetes, *n* (%)	1 (2.9)
PAH cause, *n* (%)	
Idiopathic and familial PAH	4 (11.4)
Congenital-heart-disease-associated PAH	31 (88.6)
Sinus rhythm, *n* (%)	33 (94.3)
6-Min walk distance, m	353.8 ± 131
Laboratory studies:	
Hemoglobin, g/dL	14.1 ± 2.02
Random blood glucose, g/dL	95.0 ± 18.6
Creatinine, g/dL	0.79 ± 0.2
NT-pro BNP, pg/mL	1947 ± 290.5
Medication use:	
Phosphodiesterase type 5 (PDE-5) inhibitor, *n* (%)	14 (40)
PDE-5 Inhibitor + Prostacyclin analogues, *n* (%)	21 (60)
Cardiac catheterization data	
Mean PA pressure, mmHg	46.5 ± 20.5
Pulmonary capillary wedge pressure, mmHg	8.6 ± 2.8
RA pressure, mmHg	11.5 ± 3.9
Cardiac index, L/min/m^2	2.4 ± 1.1
Pulmonary vascular resistance, WU	10.4 ± 1.3

Source: Data are presented as mean ± SD or *n* (%). WHO FC: WHO Functional Class, PAH: Pulmonary Arterial Hypertension; NT pro-BNP, N-terminal pro B-type natriuretic peptide; PA, pulmonary artery; RA, right atrium.

Baseline echocardiographic features of the study population are summarized in Table 2. Not surprisingly, the normal group showed normal LV size and function, with an average left ventricular ejection fraction of 65 ± 6.7%. No or minor left side valvular regurgitation and/or stenosis was detected and diastolic function was normal (data not shown), since there were inclusion criteria in the study.

Conventional and novel RV systolic function parameters measured using echocardiography showed that the mean values of TAPSE, FAC, RV TDI S′ velocity, and RV 3D EF remained in the normal range (Table 2) despite the high mean RVSP (87.2 ± 42.4 mmHg), using two-dimensional speckle-tracking echocardiography, the average RV GLS and RV FWS in PAH patients were −17.0 ± 5.8% and −18.6 ± 6.2%, respectively. If the ASE recommendation of −20% was used as the cut-off value, all strains were reduced, with RV GLS showing a lower value than RV FWS. This finding highlights the fact that relying solely on one strain parameter may be insufficient in assessing RV function. Comparing the strain parameters with conventional echocardiographic values in detecting RV dysfunction, we found that the RV strains (cut-off value <−20%) indicated higher rates of functional abnormality. Subclinical RV systolic dysfunction was found in 45,7% of patients according to RV GLS and 65.7% of patients according to RV FWS.

Table 2.
Echocardiographic values of the PAH study sample.

Characteristics	**Overall (*n* = 35)**
Structure:	
RA area, mm^2	23.7 ± 10.1
RA end systolic volume, ml	87.9 ± 63.3
RV wall thickness, mm	9.0 ± 3.0
RV basal dimension, mm	37.2 ± 0.8
RV mid diameter, mm	52.0 ± 15.6
RV longitudinal dimension, mm	88.1 ± 17.8
RV end diastolic area, cm^2	30.5 ± 8.4
RV end systolic area, cm^2	24.4 ± 8.0
Pericardial effusion, *n* (%)	6 (17.1)
Moderate or severe tricuspid regurgitation, *n* (%)	28 (80)
Moderate to severe pulmonary regurgitation	1 (2.8)
Ventricular Function:	
LV ejection fraction, %	65.2 ± 6.7
TAPSE, cm	2.2 ± 0.5
RV TDI S′ velocity, cm/s	13.1 ± 3.1
RV fractional area change, %	38.5 ± 8.7
Three-dimensional RV ejection fraction, %	47.9 ± 6.8
RV Speckle-Tracking Echocardiography:	
RV global longitudinal strain, %	−17.0 ± 5.8
RV free wall strain, %	−18.6 ± 6.2
Hemodynamic:	
TR Vmax, m/s	4.3 ± 1.1
Estimated RV systolic pressure, mmHg	87.2 ± 42.4
PVR by Abbas formula, WU	4.2 ± 2.9
Estimated RA pressure, mmHg	15.2 ± 5.3

Source: Data are presented as mean ± SD or *n* (%). RA, right atrium; RV, right ventricle; LV, left ventricle; TAPSE, tricuspid annular plane systolic excursion; TDI S′, tissue Doppler imaging systolic; TR Vmax, tricuspid regurgitation velocity maximum; PVR, pulmonary vascular resistance.

3.2. Echocardiographic Parameters of RV Function and Correlations with Hemodynamic Parameters through Right Heart Catheterization

The correlations between the echocardiographic parameters and hemodynamic parameters are presented in Table 3. Conventional parameters of right ventricular systolic function were found to correlate with hemodynamics by right heart catheterization. TAPSE, RV TDI S’ velocity, and FAC showed significant weak to moderate correlation with PVR (r = -0.487, *p* = 0.003; r = -0.409, *p* = 0.015; r = -0.353, *p* = 0.038, respectively). However, it was only TAPSE and RV TDI S’ velocity that exhibited significant correlation with mPAP (r = -0.455, *p* = 0.006; r = -0.379, *p* = 0.025, respectively). The three-dimensional RV ejection fraction also displayed a significant moderate correlation with mPAP and PVR (r = −0.331, *p* = 0.044; r = −0.322, *p* = 0.022, respectively).

Using 2D speckle-tracking echocardiography, both RV GLS and RV FWS exhibited significant correlations with mean pulmonary arterial pressure (mPAP) and pulmonary vascular resistance (PVR). The correlation coefficients (r) of RVGLS with mPAP and PVR were moderate (r = 0.458 and r=0.518; *p*< 0.05, respectively). RVFWS was also shown to have a moderate relationship with mPAP and PVR (r = 0.502, r = 0.507, *p* < 0.05, respectively).

Table 3.
Correlations between echocardiographic parameters of RV function and hemodynamic parameters in the PAH study sample.

RV Parameters	mPAP		PVR	
	r	*p* Value	r	*p* Value
TAPSE, cm	−0.455	0.006	−0.487	0.003
RV TDI S′ vel, m/s	−0.379	0.025	−0.409	0.015
RV FAC, %	−0.209	0.229	−0.353	0.038
RV 3D EF, %	−0.331	0.044	−0.544	0.001
RV GLS, %	0.493	0.003	0.518	0.008
RV FWS, %	0.575	0.000	0.485	0.003

Source: mPAP, mean pulmonary arterial systolic pressure; PVR, pulmonary vascular resistance; RV, right ventricle; TAPSE, tricuspid annular plane systolic excursion; RV S′, right ventricular systolic velocity; FAC, fractional area change; RV 3D EF, right ventricle three-dimensional ejection fraction; RV GLS, right ventricle global longitudinal strain; RV FWS, right ventricle free wall strain.

4. Discussion

4.1. Conventional RV Parameters and RV Longitudinal Strain

RV dysfunction is a critical concern in patients with PAH, as it significantly worsens long-term prognosis. Evaluating RV function can be challenging [17]. Although parameters such as PVR and mPAP are important during right heart catheterization, which yields essential hemodynamic data, they are invasive and impractical for frequent assessments [18] CMR is a useful imaging protocol, which provides the RV morphology and function; however, this modality is expensive, time-consuming, not accessible in many centers, and may not be indicated in some patients. Conventional 2D echocardiography remains the most common first-line imaging test in patients with PAH. It adds several Doppler-derived parameters of right heart hemodynamics and prognostic factors in patients with PAH. Nevertheless, evaluation of RV function parameters using conventional 2DE continues to be limited because of the measurement variability intrinsic to the parameters measured [6, 19].

This study confirmed the relative preservation of right ventricular function in patients with pulmonary arterial hypertension despite being in later stages and receiving suboptimal medical treatment. The majority of our patients were either on monotherapy with phosphodiesterase type 5 inhibitors (PDE 5I) or a combination of PDE 5I with prostacyclin analogues, due to drug availability limitations covered by our national insurance. Fortunately, the mean age of our research participants (34.7 ± 12.9 years) and their exercise capacity, classified according to the WHO functional class, were similar to those in a study conducted in Europe, where patients received advanced medical therapy [20].

The TAPSE, RV TDI S' velocity, and RV FAC have all been calculated using standard echocardiography. TAPSE is a simple and easy-to-obtain measurement of RV function and primarily reflects the RV longitudinal function. It has shown a weak correlation with RV 3D EF measured by CMR [21]. However, TAPSE may either over- or underestimate RV systolic function due to angle-dependent and cardiac translation. TAPSE <17 mm is very indicative of RV systolic dysfunction. Right ventricular TDI S' velocity also reflects the RV longitudinal function. Similar to TAPSE, RV S' can be influenced by heart motion, since the measurement is relative to the transducer. An RV TDI S' velocity <9.5 cm/s is suggestive of RV systolic dysfunction. While RVFAC offers an estimate of global RV systolic function that incorporates both longitudinal and circumferential function, for this reason, it has demonstrated good correlation with RVEF by CMR [22-24]. Real-time three-dimensional echocardiography has an advantage over two-dimensional echocardiography (2DE) by allowing the assessment of right ventricular (RV) volume and right ventricular ejection fraction (RVEF), regardless of the shape of the ventricle, and provides more accurate information about the morphology and function of the RV in pulmonary hypertension (PH) [7, 23]. A number of studies have demonstrated strong correlations between RVEDV, RVESV, and RVEF derived from 3DE and CMR, with a mean correlation coefficient higher than 0.9 [8, 10, 23, 24].

The myocardial structure of the right ventricle (RV) differs from that of the left ventricle (LV). The RV myocardium primarily consists of superficial and deep layers, with fibers in the superficial layer oriented, more or less, circumferentially, whereas those of the deep muscle run longitudinally from the base to the apex. The inner layers of muscle contribute about 80% to RV contraction [25]. The longitudinal shortening is very important for normal right ventricular (RV) function. Since the predominant orientation of muscle fibers in the RV is in the longitudinal plane, RV longitudinal motion is a major determinant of RV systolic function, especially in patients with pulmonary arterial hypertension (PAH). With progressive pulmonary hypertension (PH), the RV relies less on longitudinal mechanics and more on transverse wall motion, as evidenced by decreases in tricuspid annular plane systolic excursion (TAPSE), RV tissue Doppler imaging (TDI) S' velocity, and RV strain [23, 26]. Thus, RV longitudinal strain, as a method for quantifying RV systolic function, is a good marker for RV longitudinal contraction..

Two-dimensional RV speckle-tracking echocardiography is a useful tool for identifying subtle RV dysfunction in PH patients from various etiologies, including type 1 PH. This method provides relatively easy and angle-independent quantification of myocardial deformation in 2DE images. Because the predominant orientation of muscle fibers in the RV is in the longitudinal plane, the longitudinal motion of the RV is a major determinant of RV systolic function, especially in patients with PAH. During the early stages of PH, conventional RV systolic function parameters might still be preserved. In this circumstance, strain echocardiography can detect subtle RV dysfunction using RV GLS despite conventional echocardiographic parameters showing normal values of RV function [8, 26]. Some studies have already demonstrated heterogeneity in regional RV function in patients with PH, even in the absence of RVEF reduction [19, 27-29]. Therefore, assessment of subtle RV dysfunction is recommended.

Our STE-derived strain parameters showed a higher rate of RV function impairment compared to TAPSE, S′, and FAC as conventional parameters. Impaired subtle RV systolic function was found in 45.7% of patients using RV GLS and in 65.7% of patients using RV FWS. Our results were consistent with previously published studies [11]. STE imaging has the advantages of being angle-independent and not influenced by heart translational motion, which becomes a major issue in TAPSE and RV TDI S when using M-mode measurements. RV FWS demonstrated a good correlation with RVEF using CMR [17, 20] and it has been recommended as a parameter for estimating RV systolic function in the ASE guidelines [5].

4.2. RV Longitudinal Strain and Its Correlation with Invasive Hemodynamic Parameters by Right Heart Catheterization

In this study, we discovered a moderate correlation between RV GLS and RV FWS with mean pulmonary arterial pressure (mPAP) and pulmonary vascular resistance (PVR). This suggests that alterations in right ventricular function and elevated pulmonary pressure, as well as vascular resistance in the pulmonary artery, are significantly correlated. Similar findings were also reported in a study by Nizhnikava, et al. [30] who reported a correlation between RV GLS and mPAP in all participants and in PH patient groups [30]. The same findings were found in a study by Rahmianti, et al. [31] in ASD patients with PH—specifically, there was a statistically significant correlation between RV GLS and mPAP in patients with ASD secundum following RHC. A scatterplot analysis revealed a correlation between rising RV GLS and rising mPAP, and vice versa [31]. Another study by Theres, et al. [26] identified a significant relationship between right heart deformation parameters (RA and RV strain derived from 2D STE) and invasively assessed mPAP and PCWP in patients with dominant postcapillary PH [26]. Compared with the study conducted by Li, et al. [29] wherein 66 pulmonary hypertension patients exhibited a significant correlation of RVFWS with mPAP using RHC ($r = 0.597$, $p < 0.001$), this study showed a similar r value. However, it should be highlighted that our study population predominantly consisted of a CHD-PH population and not chronic thromboembolic pulmonary hypertension patients. Wright, et al. [32] carried out a prospective study on 187 PAH patients at two time points. A highly significant correlation between Δ RVFWS and Δ PASP was discovered. It was implied by these results that as the RV function deteriorates, PH will be found to be progressing. Nevertheless, in spite of the association seen between RV strain and mPAP, r values in our study were moderate.

The relationship between mPAP and RV GLS may be explained by the main longitudinal reorientation of RV myocyte aggregates provoked by pressure overload [26, 33]. Chronic RV overpressure triggers an adaptive remodeling response, which leads to compensatory hypertrophy and tends to preserve RV volume and function. The occurrence of maladaptive remodeling, characterized by eccentric hypertrophy, progressive RV dilatation and dyssynchrony, and the persistence of stroke volume via the Frank–Starling mechanism (heterometric adaptation), occurs when this homeometric adaptation fails, and contractility can no longer increase to compensate for the increased afterload. Subsequently, clinical decompensation develops later in life [2, 25]. The pressure-overload-mediated geometric change of the RV (from crescent shape to a circular cross section) might be why RV strain was a significant predictor in the present study [9, 26]. This may also explain the observation that in our PAH patients, RVGLS and RV FWS showed comparable correlations with mPAP.

PVR, as a consequence of structural changes in the pulmonary arteries, is elevated and leads to RV pressure overload and RV systolic dysfunction in PAH. Chronic RV pressure overload has a direct impact on RV longitudinal systolic function and results in the impairment of RV GLS Ratri, et al. [34]. Sachdev, et al. [13] also reported a markedly reduced RV free wall strain (-15±5%) in 80 patients with PAH. He also found that patients with reduced RV FWS > -12.5% had an increased mPAP and PVR [19]. In our study, the mean RV GLS was -17.0 ± 5.8% and the RV FWS was 18.6 ± 6.2%. These values are higher than those reported by Sachdev et al., perhaps because most subjects in our study had normal systolic RV function. Nonetheless, we found moderately significant correlations of RV GLS and RV FWS with PVR. Recent developments in medical therapies have resulted in improved hemodynamics, exercise capacity, and prognosis in patients with PAH [35-37]. These may indicate that RVLS can be a useful non-invasive indicator in the serial assessment of RV mechanical function in PAH patients.

4.3. Study Limitations

This study was a cross-sectional, single-center investigation involving patients with pulmonary arterial hypertension (PAH), with more than half of the sample having an etiology of congenital heart disease. This could have potentially introduced a selection bias, given the small number of other PAH etiologies to define distinct patterns of right ventricular (RV) subclinical dysfunction. Using two-dimensional (2D) speckle tracking to evaluate the RV lateral wall, as seen in the four-chamber view, might have affected the accuracy of RV function measurement compared to cardiac magnetic resonance (CMR). Three-dimensional (3D) speckle-tracking imaging of the RV, in comparison with CMR, will likely be the next step toward the early detection of RV dysfunction.

5. Conclusions

In conclusion, STE-derived parameters are potentially more capable of detecting subtle RV systolic dysfunction than conventional echocardiographic indices. RV longitudinal strain, particularly RV GLS and RV FWS, exhibited significant correlations with hemodynamic parameters through right heart catheterization.

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