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Echocardiography

ORIGINAL INVESTIGATIONS

Correlation between Pulmonary Artery Pressure Measured by Echocardiography and Right Heart Catheterization in Patients with Rheumatic Mitral Valve Stenosis (A Prospective Study)

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Introduction: Right heart catheterization (RHC) remains the gold standard for hemodynamic assessment of the right heart and pulmonary artery. However, this is an invasive tool, and noninvasive alternatives such as transthoracic echocardiography (TTE) are preferable. Nonetheless, the correlation between measurements by TTE and RHC are debated. In this study, we prospectively examined the correlation between systolic and mean pulmonary artery pressures (sPAP and mPAP) measured by RHC and TTE in patients with hemodynamically significant rheumatic mitral stenosis (MS). Material and Methods: Three hundred patients with hemodynamically significant MS undergoing TTE who were scheduled to undergo RHC within 24 hours were analyzed. PAP measurements were taken for all patients by RHC ($sPAP_{RHC}$, $mPAP_{RHC}$). Maximum velocity of tricuspid regurgitation (TR) jet obtained by continuous-wave Doppler with adding right atrial (RA) pressure was used for measuring sPAP by TTE ($sPAP_{TRVmax}$). Mean PAP was measured using either pulmonary artery acceleration time ($mPAP_{PAAT}$) method or by adding RA pressure to velocity–time integral of TR jet ($mPAP_{TRVTI}$). Results: A good correlation between $sPAP_{RHC}$ and $sPAP_{TRVmax}$ ($r = 0.89$, $P < 0.001$), between $mPAP_{RHC}$ and $mPAP_{PAAT}$ ($r = 0.9$, $P < 0.001$), and between $mPAP_{RHC}$ and $mPAP_{TRVTI}$ ($r = 0.92$, $P < 0.001$) was found. Sensitivity and specificity of $sPAP_{TRVmax}$ in detecting pulmonary hypertension (PH) were 92.8% and 86.6% and of $mPAP_{PAAT}$ were 94.1% and 73.3%, respectively. Conclusion: The noninvasive assessment of sPAP and mPAP by TTE correlates well with invasive measurements and has an acceptable specificity and sensitivity in detecting PH in patients with hemodynamically significant MS. (Echocardiography 2016;33:7–13)

Key words: pulmonary artery pressure, right heart catheterization, echocardiography

Pulmonary hypertension (PH), a syndrome characterized by increased pulmonary vascular resistance and remodeling, is associated with significant morbidity and mortality, which are directly related to cardiac function.[1] Transthoracic Doppler echocardiography (DE), because of its noninvasive nature, is commonly used to estimate pulmonary pressures. However, studies on its reproducibility and reliability in estimating the systolic pulmonary artery pressure (sPAP), independently of the underling cardiopulmonary disease, have ended with conflicting results.[2–16] Right heart catheterization (RHC) is the technique of choice and the gold standard for the diagnosis and evaluation of patients with PH, because it provides an accurate measurement of pulmonary pressures. However, its invasive nature makes it unsuitable for frequent and repeated use. DE is recommended as the initial noninvasive modality in the screening and evaluation of PH.[17] Echocardiography can be used to evaluate right-sided chamber size and function and the presence of pericardial effusion, which are known to impact survival.[18–20]

Frequently, DE is used to estimate the right ventricular (RV) systolic pressure by estimating the pressure gradient between the RV and the right atrium (RA) using the modified Bernoulli equation, $4v^2$, where v equals the maximum velocity of the tricuspid regurgitant (TR) jet (TRVmax). An estimated RA pressure (RAP) is added to this number to approximate the RV systolic pressure, which equals the sPAP in the absence of pulmonic stenosis. Recently, Aduen et al.[21] proposed a novel and

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simple method to estimate mean PAP (mPAP) on the basis of the addition of RA pressure to the RV-RA mean systolic gradient obtained by tracing the TRVmax jet profile. This method was validated in 102 patients, comparing it with simultaneous RHC. Mahan and Dabestani et al.[22,23] in two separate studies showed that the mPAP may also be estimated using pulmonary artery acceleration time (PAAT) measured by pulsed DE of the pulmonary artery in systole. PAAT is a particularly attractive alternative to the TRVmax-dependent method, because it does not rely on the presence of an anatomic defect or valvular regurgitation and is therefore measurable in the vast majority of individuals.

Pulmonary hypertension is a common complication of mitral valve disease and may affect as many as 73% of patients depending on disease severity.[24,25] There has been no previous systematic study on the correlation between RHC and DE in estimating both systolic and mean PAP in patients with hemodynamically severe rheumatic MS. The objective of this study was to prospectively evaluate the diagnostic accuracy of DE parameters for the detection of PH and to correlate with invasive RHC measurements in consecutive patients referred to our tertiary center.

Materials and Methods:

Patients:

This was a prospective study in which we evaluated 420 symptomatic patients with hemodynamically significant rheumatic MS (mitral valve area ≤ 1.5 cm^2) who were referred to our tertiary center for percutaneous balloon mitral valve valvotomy (PBMV) between September 2010 and August 2012. RHC was performed within 24 hours of the TTE. Patients with pulmonary stenosis were excluded. Demographic and clinical data were collected for each patient at study entry. The study was approved by our Institutional Review Board, and all patients provided informed consent.

Echocardiographic Study:

A commercially available VIVID 7 (GE Healthcare, Horten, Norway) cardiac ultrasound system with 2.5- and 3.5-MHz multifrequency transducers was used. All the DE measurements were performed with a sweep speed of 100 to 200 mm/sec. All echocardiographic and DE studies were performed by an experienced board-certified echocardiographer (MT). The following echocardiographic parameters were systematically assessed:

$sPAP_{TRVmax}$: RVSP was estimated from the TR jet velocity profile using the modified Bernoulli equation.[2] To obtain the best possible alignment between TR jet and the continuous-wave Doppler ultrasound beam, color Doppler flow mapping was used. All patients were examined using several nonstandard projections to record the highest TR velocity. Patients with trace or eccentric regurgitation were excluded from the study because the peak TR velocity was difficult to obtain precisely. By adding the mean RAP to the RVSP, $sPAP_{TRVmax}$ was achieved. No contrast methods were used. In case of atrial fibrillation, five beats were used for averaging velocities. Echocardiographic RAP estimation was performed on the basis of inferior vena cava (IVC) diameter and collapsibility. IVC diameter was measured within 2 cm of the RA at end-expiration and end-diastole and at end-inspiration[26] or during a "sniff" maneuver. If the IVC was not adequately visualized, the patient was excluded. RAP was estimated to be 3 mmHg when the IVC diameter was <21 mm with >50% collapsibility, 8 mmHg when the IVC diameter was <21 mm with <50% collapsibility, and 15 mmHg when the IVC diameter was >21 mm with <50% collapsibility.[27]

$mPAP_{TRVTI}$: Estimated RA pressure was added to the velocity–time integral of the TR jet obtained by continuous-wave Doppler to calculate a mean systolic pressure.[21] Patients with trace or eccentric regurgitation were excluded, as mentioned before.

$mPAP_{PAAT}$: Pulsed-wave Doppler interrogation of the proximal PA was then performed in the parasternal short-axis view with the sample volume placed at the annulus of the pulmonary valve. The sample volume was placed at the pulmonary valve annulus and not more proximally in the RV outflow tract to maximally align blood flow and Doppler interrogation. PAAT was defined as the interval between the onset of systolic PA flow and peak flow velocity, whereby $mPAP_{PAAT} = 79 - (0.45 \times PAAT)$.[22] In cases with PAATs < 120 ms, the following formula was used: $90 - (0.62 \times PAAT)$.[23]

Right-Sided Heart Catheterization:

All RHC measurements made during the study were performed by interventional cardiologists experienced in both cardiac catheterization and PH (BS, NA). Close attention was paid to ensure proper leveling and zeroing of transducers during each study. An appropriate response on the monitor to vertical movement of the catheter was required before insertion into the patient, and a rapid flush test was performed after insertion. All waveforms were evaluated to ensure that they were of high quality, and all hemodynamic

measurements (RAP, $sPAP_{RHC}$, $mPAP_{RHC}$) were made at end-expiration. The varying RR intervals in patients with atrial fibrillation may cause varying degrees of ventricular filling with each beat and result in wide variation in systolic pressure peaks. It was for this reason that the data from 10 consecutive beats were averaged in these patients.[28] The physicians performing the RHC were blinded to the DE data.

Statistics:

Descriptive statistics were presented using mean (SD) for continuous variables and number (%) for categorical variables. Relationships between RHC- and DE-derived hemodynamics were assessed using the Pearson correlation. We used Bland–Altman analyses to evaluate the agreement between DE estimates of sPAP/mPAP with those same values as determined by RHC. To interpret the results of the Bland–Altman analyses clinically, DE estimates of sPAP/mPAP would be considered accurate if the differences within the 95% limits of agreement between DE and RHC measurements of sPAP/mPAP were small and not considered clinically relevant. Alternatively, it would be unacceptable to consider DE estimates of sPAP/mPAP as accurate compared with RHC measurements of sPAP/mPAP if the 95% limits of agreement were large and thought not to be of clinical relevance.[29] Receiver operating characteristic (ROC) curves were created to assess the utility of each of the DE methods (PAAT and TRVTI) in diagnosing PH, with PH defined as sPAP ≥35 or mPAP ≥25 mmHg derived from RHC; AUC was estimated along with 95% CIs. Bland–Altman analysis was carried out using MedCalc version 12.7.7.0. All other statistical analysis was performed with SPSS version 16.0 (SPSS Inc., Chicago, IL, USA), and finally, the STATA software STATA Corp., College Station, TX, USA) was used to compare calculated AUC for PAAT and TRVTI. Significance was defined as 2-tailed $P < 0.05$.

Results:

In this study, pulsed-wave Doppler imaging of the main pulmonary artery was sufficient to measure PAAT in 98.6% of patients (414 of 420). In contrast, 27.1% (114 of 420) either did not have sufficient TR (32 patients) or had an eccentric TR jet precluding precise measurement of TRVmax (82 patients), which were excluded from the study. As such, 300 individuals were retained in the final analysis. The mean age was 49.9 years (range 15–75), and 69.3% were female (208 of 300). Atrial fibrillation or flutter was present in 38% of patients (114 of 300), while the remaining 62% were in normal sinus rhythm. Table I summarizes the results of measurements of PAP by RHC and DE. A comparison between these findings showed a good correlation between $sPAP_{RHC}$ and measured $sPAP_{TRVmax}$ (Pearson correlation = 0.89, $P < 0.001$). There was also a good correlation between $mPAP_{RHC}$ and $mPAP_{PAAT}$ (Pearson correlation = 0.90, $P < 0.001$). Correlation coefficient between $mPAP_{RHC}$ and $mPAP_{TRVTI}$ was $r = 0.92$, and it showed a significant correlation between them ($P < 0.001$). A subgroup analysis was performed in patients with no TR but good PAAT by DE, which also showed a good correlation between $mPAP_{RHC}$ and $mPAP_{PAAT}$ (Pearson correlation = 0.90, $P < 0.001$) and between $sPAP_{RHC}$ and $sPAP_{PAAT}$ (Pearson correlation = 0.87, $P < 0.001$). For qualitative comparison between $sPAP_{RHC}$ and measured $sPAP_{TRVmax}$, a cutoff point of 50 mmHg was considered. By RHC, 132 patients (49.6%) had a sPAP under 50 mmHg. By DE, 137 patients (51.5%) had sPAP under 50 mmHg. Agreement between these two methods was 85.3%. The measured kappa score was 71% ($P < 0.001$), which also showed a good agreement. Figure 1

TABLE I

Measurements of Systolic and Mean Pulmonary Artery Pressures by Right Heart Catheterization and Doppler Echocardiography

Method	Mean ± SD (range) mmHg
sPAP* by TRVmax†	53.78 ± 19.19 (15–120)
sPAP* by RHC‡	53.42 ± 19.92 (20–145)
mPAP* by RHC‡	35.51 ± 13.01 (10–70)
mPAP* by PAAT§	37.10 ± 12.98 (11–78)
mPAP* by TRVTI¶	35.88 ± 13.07 (10–77)

*Systolic/mean pulmonary artery pressure.
†Tricuspid regurgitation maximum velocity.
‡Right heart catheterization.
§pulmonary artery acceleration time.
¶Tricuspid regurgitation velocity–time integral.

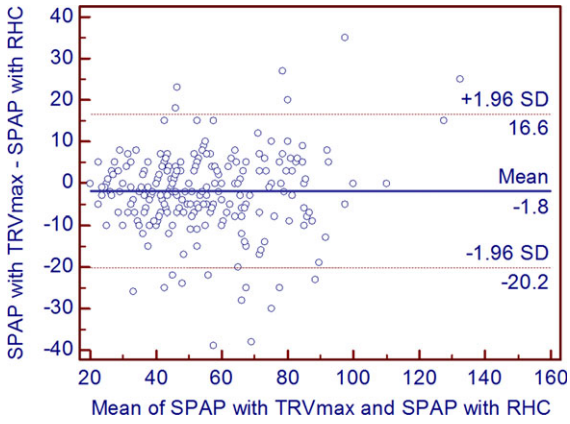

Figure 1. The Bland–Altman plot showing the agreement between $sPAP_{RHC}$ and measured $sPAP_{TRVmax}$.

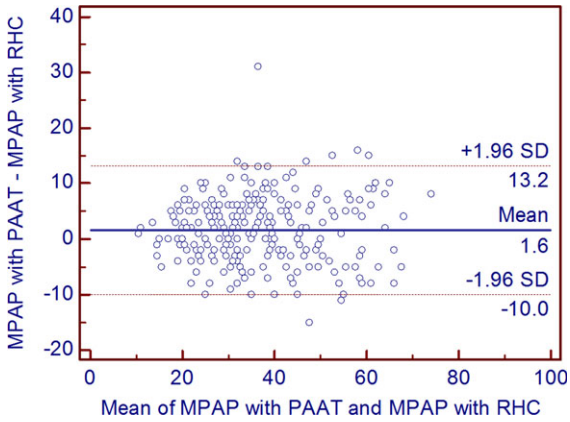

Figure 2. The Bland–Altman plot showing the agreement between measured $mPAP_{RHC}$ and $mPAP_{PAAT}$.

is the Bland–Altman plot showing the agreement between $sPAP_{RHC}$ and measured $sPAP_{TRVmax}$, with only 18 cases out of the range of 95% limits of agreement between DE and RHC measurements of sPAP. Figure 2 is the Bland–Altman plot showing the agreement between measured $mPAP_{RHC}$ and $mPAP_{PAAT}$, with only 8 cases out of the range of 95% limits of agreement between DE and RHC measurements of mPAP. And finally, Figure 3 shows the Bland–Altman plot of agreement between measured $mPAP_{RHC}$ and $mPAP_{TRVTI}$, with only 11 cases out of the range of 95% limits of agreement between DE and RHC measurements of mPAP.

Right heart catheterization is considered the gold standard for detecting PH. We measured the sensitivity and specificity of DE for detection of patients with PH defined as $sPAP_{RHC} \geq 35$ mmHg for this purpose. PH was present in 87.7% of patients by RHC and in 83.8% of patients by using TRVmax, leading to sensitivity, specificity, positive predictive, and negative predictive values of 92.8%, 86.6%, 98.2%, and 60.5%, respectively, for the detection of PH by DE. When we defined PH as $mPAP_{RHC} \geq 25$ mmHg, PH was present in 80.7% of patients. By the PAAT method, mPAP ≥25 mmHg was present in 84% of patients, leading to sensitivity, specificity, positive predictive, and negative predictive values of 95.5%, 63.8%, 91.7%, and 77.1%, respectively, for the detection of PH by $mPAP_{PAAT}$. When we used the other DE method ($mPAP_{TRVTI}$), 82.7% of patients were diagnosed, leading to sensitivity, specificity, positive predictive, and negative predictive values of 94.1%, 73.3%, 94.5%, and 71.7%, respectively, for the detection of PH by this method. Both methods of DE had acceptable sensitivities, but measurements by PAAT showed more false-positive results than the TRVTI method (%36.2 vs. %26.7), which may reflect TRVTI as the relatively preferred DE method for measuring mPAP. But the comparison of AUC for mPAP measurements by PAAT and TRVTI showed no significant differences or superiority of either method in detecting PH (AUC for $mPAP_{PAAT}$ and $mPAP_{TRVTI}$ was 0.928 and 0.941, respectively, $P = 0.58$).

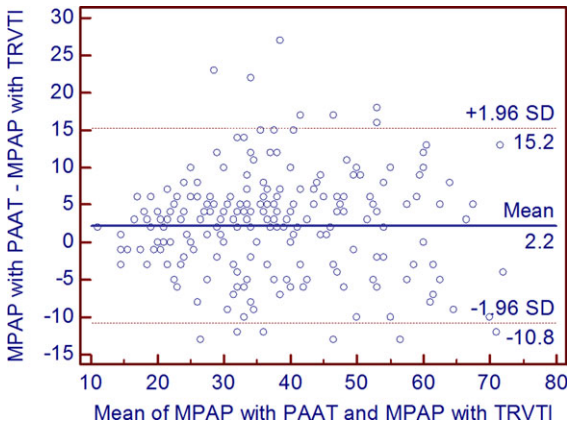

Figure 3. The Bland–Altman plot showing the agreement between measured $mPAP_{RHC}$ and $mPAP_{TRVTI}$.

Inter-observer coefficients of variation for RHC measurements and intra-observer coefficients of variation for echocardiographic parameters were found to be less than 5% and nonsignificant. Shapiro–Wilk test showed that the distribution of all quantitative variables was normal ($P > 0.05$).

Discussion:

This prospective study evaluated the utility of DE for the estimation of PAP in a large population of patients with hemodynamically significant rheumatic MS referred for PBMV at a tertiary referral heart center. All patients underwent DE and RHC sequentially and within a short time frame (<24 hour). The noninvasive assessment of sPAP and mPAP by DE correlated well with invasive measurements and had high levels of specificities and sensitivities in detecting PH.

Many studies have been carried out in the past that have tried to compare DE and RHC for evaluation of sPAP and mPAP, in various patient populations, ending with conflicting results.[2–16] Very recently, Lafitte et al.[30] reported a retrospective study on a heterogeneous group of patients with different underling cardiopulmonary diseases ($n = 310$) comparing DE and RHC in estimation of sPAP and diagnosis of PH within a single hospitalization. The DE method ($sPAP_{TRVmax}$) was exactly the same we used in our study. Similar to our results, data analysis revealed a strong correlation ($r = 0.80$, $P < 0.00001$) between these two methods in estimation of sPAP. The sensitivity, specificity, and accuracy were 88%, 83%, and 86%, respec-

tively, for the diagnosis of PH. In another small prospective study with 42 patients, Tian et al.[31] also showed a good correlation between RHC and DE measurements for sPAP ($r = 0.96$) and mPAP ($r = 0.88$). On the contrary, Fisher et al.[32] studied 63 patients with emphysema, being evaluated for lung volume reduction surgery, and found a sensitivity of 60%, specificity of 74%, positive predictive value of 68% and a negative predictive value of 67% for DE compared with RHC in estimation of sPAP and mPAP. Bland–Altman analysis also revealed a week correlation between these two methods. The limitations of this study were as follows: Data were collected retrospectively; measures of right ventricular function, dimensions, or wall thickness were not recorded which when available to the echocardiographers can influence their interpretation of the presence or absence of PH[32]; echocardiography was performed by technicians who were not specially trained in image acquisition for the respecified manual of procedures; equipment was not uniform; studies were interpreted on-site by local cardiologists; and finally, the method used for the estimation of RAP was different than the one recommended by the latest guidelines.[27] The same investigators subsequently conducted another small prospective study ($n = 65$) on the accuracy of DE for estimating PAP and cardiac output in patients with various forms of PH who underwent comprehensive DE within one hour of RHC.[33] Despite the very short period of performing these two methods, DE estimates for RAP and sPAP differed significantly from those determined by RHC, as assessed by Bland–Altman analysis, with a tendency to both overestimate and underestimate the sPAP. Underestimations were larger in magnitude and more often significantly misclassified the severity of PH. The main limitation of this study was that fair- or poor-quality Doppler jets across the tricuspid valve were included in the measurements. Of note, 10 of 12 (83%) underestimates greater than 20 mmHg were associated with these suboptimal signals, suggesting inadequate or incomplete resolution of the maximal jet velocity as the cause of underestimation. To avoid this pitfall, we excluded patients with suboptimal TR jet and/or if the IVC was not adequately visualized, and used a different and updated method for RAP estimation.[27] In another study, Rich et al.[34] performed a prospective study on 160 consecutive patients referred for presumed PH and who subsequently underwent both RHC and DE within 30 days. Using the predefined definition of an inaccurate DE estimation of sPAP as ± 10 mmHg different from sPAP measured during RHC, they found that DE was inaccurate 50.6% (81/160) of the time [overestimation in 40.7% (33/81) of cases and underestimation in 59.3% (48/81) of cases]. Using the predefined definition of an inaccurate DE estimate of RAP as ± 2.5 mmHg different from RAP measured during RHC, they found that DE was inaccurate in 58.7% (64/109) of the cases (overestimation in 64.1% (41/64) of cases and underestimation in 35.9% (23/64) of the cases). To address the possibility that variations in hemodynamics occurring during the 30-day interval between RHC and DE may affect their findings, they prospectively enrolled an additional 23 consecutive patients with PH referred for RHC. DE imaging was performed on each of these patients in the cardiac catheterization laboratory simultaneous to the invasive hemodynamic measurements made during the RHC. Although carried out in an optimal setting, the RAP measurement method was different from ours and all the DE measurements were performed by echocardiography technicians.

Data on correlation between DE and RHC in patients with hemodynamically significant rheumatic MS are very scarce and only limited for comparing sPAP measurements. Toufan et al.[35] reported a retrospective study of 166 patients with MS who were candidate for PBMV and found a significant correlation between measured $sPAP_{TRVmax}$ and $sPAP_{RHC}$ when performed on the same day ($r = 0.718$; $P = 0.0001$). Unfortunately, the method for RAP measurement was not mentioned and they did not use Bland–Altman analysis to evaluate the agreement between estimates of sPAP by these methods. Furthermore, studies on comparing measured mPAP by DE and RHC are also limited.[21–23] To the best of our knowledge, this is the first study on the comparison of three different DE methods for the estimation of sPAP/mPAP with that measured by RHC in patients with hemodynamically significant MS. We found a significant correlation between these two methods, along with an acceptable specificity and sensitivity in detecting PH by DE.

The main reasons for the contradictory results in studies on correlation between DE and RHC in PAP measurements and detecting PH are differences in the underlying diseases, the skill of the operator, equipment quality, echocardiographic methods, and exclusion criteria. Before conducting our study, we carefully studied previous studies and tried to avoid their potential limitations. We believe that the important reasons for our positive results are as follows: (1) We had a homogenous study group with all having hemodynamically significant rheumatic MS; (2) an experienced board-certified echocardiographer performed all the echocardiographic studies; (3) patients with trace or eccentric regurgitation were excluded from the study because these would

result in error in obtaining the peak TR velocity precisely; (4) for the estimation of RAP, if the IVC was not adequately visualized, the patient was excluded; (5) and all RHC measurements made during the study were performed by interventional cardiologists experienced in both RHC and PH. Other authors have reached to a similar conclusion that when all conditions required for performing an optimal DE imaging are met – namely sufficient TR for interrogation, proper Doppler alignment, optimal visualization of the peak of the TR jet, and accurate RAP estimation – this method indeed correlates strongly with invasive PAP assessment.[3,5]

Limitations:

We did not use saline contrast in our study. Many studies have demonstrated that inadequate TR velocity signals can be enhanced with the use of contrast, and dramatically improve the correlation between Doppler-measured and catheter-measured PAP.[36,37] Furthermore, we did not measure cardiac output and RV function in our patients. As both can affect pulmonary artery flow, we remain uncertain about the accuracy of PAAT in patients with high cardiac output due to exercise or systemic vasodilation and RV systolic dysfunction.[38] DE and RHC were not carried out simultaneously, and this could have affected our results. However, a minimum of two studies could not prove that the time laps between these measurements could result in disagreement.[32,39] The prospective, controlled, single-center nature of this study limits generalization. However, given that this study represents the experience of a high-volume center, exclusively by trained board-certified echocardiographers, it is unlikely that our results represent a substantial outlier among other echocardiography laboratories. And finally, this study was conducted on a homogenous group of patients with MS and PH. It remains speculative whether these results can be applied to other patient groups with suspected or proven PH, although we strongly believe that by applying our exclusion criteria, described previously, and performing the measurements by experienced echocardiographers, a good correlation between invasive and noninvasive measurement of PAP in other patient groups will be found as well.

Conclusion:

The noninvasive assessment of sPAP and mPAP by DE correlates well with invasive measurements and has an acceptable specificity and sensitivity in detecting PH in patients with hemodynamically significant MS. The information obtained from a satisfactory DE study in this subset of patients can be used for diagnostic and therapeutic purposes without the need for the alternative RHC, which is expensive and more importantly invasive.

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