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Echocardiographic Doppler Estimation of Pulmonary Artery Pressure in Critically Ill Patients with Severe Hypoxemia

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Background: **In spontaneously breathing cardiac patients, pulmonary artery pressure (PAP) can be accurately estimated from the transthoracic Doppler study of pulmonary artery and tricuspid regurgitation blood flows. In critically ill patients on mechanical ventilation for acute lung injury, the interposition of gas between the probe and the heart renders the transthoracic approach problematic. This study was aimed at determining whether the transesophageal approach could offer an alternative.**

Methods: **Fifty-one consecutive sedated and ventilated patients with severe hypoxemia (arterial oxygen tension/fraction of inspired oxygen < 300) were prospectively studied. Mean PAP measured from the pulmonary artery catheter was compared with several indices characterizing pulmonary artery blood flow assessed using transesophageal echocardiography: preejection time, acceleration time, ejection duration, preejection time on ejection duration ratio, and acceleration time on ejection duration ratio. In a subgroup of 20 patients, systolic PAP measured from the pulmonary artery catheter immediately before withdrawal was compared with Doppler study of regurgitation tricuspid flow performed immediately after pulmonary artery catheter withdrawal using either the transthoracic or the transesophageal approach.**

Results: **Weak and clinically irrelevant correlations were found between mean PAP and indices of pulmonary artery flow. A statistically significant and clinically relevant correlation was found between systolic PAP and regurgitation tricuspid flow. In 3 patients (14%), pulmonary artery pressure could not be assessed echocardiographically.**

Conclusions: **In hypoxemic patients on mechanical ventilation, mean PAP cannot be reliably estimated from indices characterizing pulmonary artery blood flow. Systolic PAP can be estimated from regurgitation tricuspid flow using either transthoracic or transesophageal approach.**

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IN spontaneously breathing cardiac patients, an accurate transthoracic echocardiographic estimation of mean pulmonary artery pressure (mPAP) can be obtained by measuring indices characterizing pulmonary artery blood flow.[1–3] In the presence of a tricuspid regurgitation, systolic pulmonary artery pressure (sPAP) can also be accurately estimated by measuring the peak velocity of the retrograde tricuspid flow.[4,5] In critical care conditions, however, two factors may render such methods ineffective. First, transthoracic ultrasound transmission may be seriously hampered by the interposition of gas between the probe and the heart in mechanically ventilated patients. As demonstrated in anesthetized patients undergoing cardiac surgery,[3] the transesophageal approach could be an attractive alternative for measuring mPAP from the Doppler study of pulmonary blood flow. Second, tricuspid regurgitation may be absent in patients with normal cardiac function, precluding the evaluation of sPAP.

The impact of positive-pressure ventilation and preload and afterload changes on indices of pulmonary blood flow may represent additional confounding factors. Pulmonary hypertension is a marker of acute lung injury and appears as resulting from inflammatory vasoactive mediators release, alveolar hypoxia, endothelial swelling, and capillary microthrombosis. Although it does not improve clinical outcome of patients with acute respiratory distress syndrome,[6,7] inhaled nitric oxide is commonly administered to increase arterial oxygen tension (Pao_2), partially relieve pulmonary hypertension, and improve cardiac output in the presence of right ventricular dysfunction.

The aims of the current study were to assess whether, in critically ill ventilated patients, estimation of the pulmonary artery pressure or its variations induced by inhaled nitric oxide could be accurately predicted using transesophageal echocardiography from either (1) Doppler study of pulmonary artery blood flow or (2) Doppler measurement of peak velocity of tricuspid regurgitation. We also evaluated the value of right ventricle dimensions and septal dyskinesia for identifying pulmonary hypertension.

Materials and Methods

Patients

Fifty-one consecutive patients admitted to the surgical intensive care unit of la Pitié-Salpêtrière hospital (Paris,

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France) for severe hypoxemia were prospectively studied. Inclusion criteria were (1) Pa_{O_2}/fraction of inspired oxygen (F_{IO_2}) less than 300, (2) presence of a pulmonary artery catheter inserted by the physician in charge for clinical reasons independent of the study protocol, and (3) indication for a transesophageal echocardiographic evaluation by the physician in charge for clinical reasons independent of the study protocol. Because nothing more than routine hemodynamic evaluation was performed in the current study, no informed consent was required from patients' next of kin. Exclusion criteria were esophageal and gastric pathology, cervical spine instability, lack of sinus rhythm, right or left bundle branch block, and previous cardiac surgery.

For each individual, simultaneous transesophageal Doppler study of the pulmonary artery flow and recording of pulmonary artery pressures were performed. In 20 patients for whom the pulmonary artery catheter was no longer required, transesophageal and transthoracic Doppler study of tricuspid regurgitation flow were performed immediately after catheter removal. In 41 patients, a nitric oxide test was performed, aimed at improving arterial oxygenation and lowering pulmonary artery pressure. Transesophageal echocardiographic measurements of pulmonary artery flow were simultaneously performed with the recording of pulmonary artery pressure obtained from the Swan Ganz catheter before and after nitric oxide inhalation.[8,9]

Respiratory Measurements

During the study period, all patients were anesthetized with continuous intravenous infusion of 5 $\mu g \cdot kg^{-1} \cdot h^{-1}$ fentanyl and 0.1 $mg \cdot kg^{-1} \cdot h^{-1}$ midazolam and paralyzed with 0.5 mg/kg atracurium. All patients were ventilated using controlled mechanical ventilation (Horus ventilator; Taema, Anthony, France). Tidal volume was set between 6 and 9 ml/kg, and respiratory rate was adjusted by the clinician in charge of the patient to achieve arterial carbon dioxide tension (Pa_{CO_2}) values between 40 and 50 mmHg according to recent recommendations.[8,9] Inspiratory time and F_{IO_2} were maintained at 33% and 1, respectively, throughout the study period. Selection of positive end-expiratory pressure and use of almitrine were determined independently by the physician in charge of the patients according to previously published guidelines[9–11] and remained unchanged during the protocol.

Hemodynamic Measurements

All patients were monitored using a radial or femoral arterial catheter and a fiberoptic thermodilution pulmonary artery catheter allowing the continuous monitoring of mixed venous oxygen saturation and the repetitive measurement of cardiac output using the semicontinuous thermodilution technique (CCO/Sv_{O_2}/VIP TD catheter; Baxter Healthcare Co., Irvine, CA). During the study period, cardiac output, systemic arterial pressure, right atrial pressure, pulmonary artery pressure, pulmonary capillary wedge pressure, and airway pressure were continuously recorded using a BIOPAC MP100 system (Biopac System, Goleta, CA). Pulmonary vascular resistance index (PVRI) was calculated as PVRI = (mPAP − pulmonary capillary wedge pressure) × 80/cardiac index. Fluid-filled transducers were positioned at the midaxillary line and connected to the different lines of the pulmonary artery catheter. All recordings were reviewed by an investigator unaware of the echocardiographic data and were averaged over five cardiac cycles at end-expiration.

Echocardiographic Studies

In each patient lying supine, complete transesophageal echocardiography was performed using a HP-SONOS 5500 (Hewlett Packard, Andover, MA). Images were stored digitally on magneto-optical disks for latter playback and analysis. Transthoracic and transesophageal echocardiographic data were obtained using standard views and techniques.[12]

Pulmonary artery flow was examined *via* the midesophageal ascending aortic short axis view. The pulmonary artery blood flow was recorded by pulsed Doppler with the sample volume into the center of the main trunk of the pulmonary artery beyond the pulmonary valve. The ultrasound beam was placed as parallel as possible to the pulmonary flow.

Using the transthoracic approach, the tricuspid regurgitation flow was assessed by apical and subcostal four chamber view.[5] Using the transesophageal approach, the tricuspid regurgitation flow was assessed by midesophageal four chamber, right ventricular inflow–outflow and deep transgastric long axis views. Color flow Doppler imaging was used to detect the tricuspid regurgitation and to determine the angle of flow for the better alignment of the ultrasonic beam. The tricuspid regurgitation flow was recorded by continuous Doppler.

Right ventricle end-systolic and end-diastolic areas and left ventricle end-diastolic area were measured from the four chamber view. From the transgastric view, septal motion at late systole and early diastole was carefully studied over several respiratory cycles to detect septal dyskinesia. Septal dyskinesia was defined by septal flattening or paradoxical septal motion, *i.e.*, leftward septal displacement.[13]

Echocardiographic measurements were performed offline by an observer unaware of clinical data and other hemodynamic measurements. All measurements were made at end-expiration over five consecutive cardiac cycles. The pulmonary artery inflow velocity was analyzed for peak velocity, velocity time integral, preejection time (pET: the time interval from onset of the electrocardiographic Q wave to the initial systolic upward deflection of the pulmonary artery flow velocity

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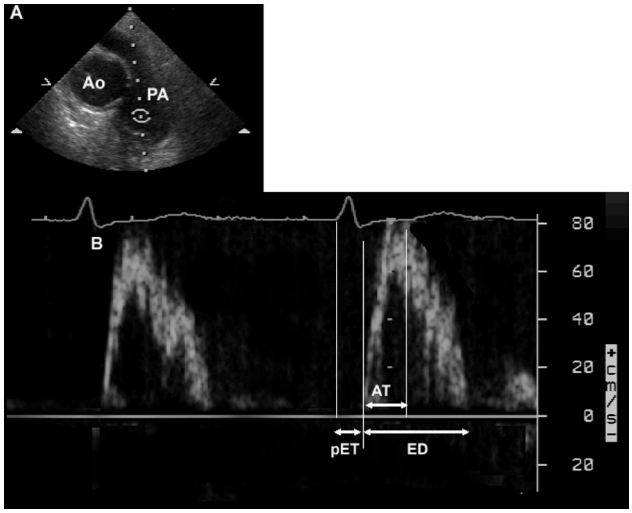

Fig. 1. (*A*) Pulmonary artery flow was obtained *via* the midesophageal ascending aortic short axis view. Ao = transversal section of ascending aorta; PA = main trunk of pulmonary artery. (*B*) Pulmonary artery flow recorded by pulsed Doppler. AT = acceleration time (time interval between onset and peak of pulmonary artery flow velocity); ED = ejection duration; pET = preejection time (time interval from onset of electrocardiographic Q wave to initial systolic upward deflection of pulmonary artery flow).

curve), acceleration time (AT: the time interval between the onset and peak of pulmonary artery flow velocity), and ejection duration (ED: the time interval from the onset to termination of the systolic pulmonary flow velocity) (fig. 1).

Systolic pulmonary artery pressure was estimated from peak velocity of tricuspid regurgitation using Bernoulli equation: sPAP = 4 × (peak velocity of tricuspid regurgitation)^2 + right atrial pressure. Central venous pressure measured through central venous line was considered as equivalent to right atrial pressure.

Right ventricular enlargement was studied on the four chamber view and was defined by right ventricle end-diastolic area/left ventricle end-diastolic area greater than 60%.[13] An acute cor pulmonale was defined by the association of a septal dyskinesia with a right ventricle enlargement.[13]

Nitric Oxide Inhalation

Nitric oxide inhalation was synchronized to inspiration using an OPTI-NO (Taema, Antony, France) to achieve an inhaled concentration of 2–4 ppm according to previous recommendations.[14,15] All hemodynamic and echocardiographic measurements previously described were performed before and during nitric oxide inhalation.

Statistical Analysis

All data are expressed as mean ± SD. Normality of the data distribution was assessed by a Kolmogorov-Smirnov test.

The main goal of the study was to determine whether echocardiography could replace right heart catheterization for measuring pulmonary artery pressure, using two different approaches: the transesophageal and transthoracic measurement of sPAP by measuring the tricuspid flow regurgitation and the transesophageal measurement of mPAP by measuring different parameters characterizing pulmonary blood flow. The current study was considered as a pilot study in the absence of previous publications aimed at verifying whether results obtained in spontaneously breathing cardiac patients do apply to critically ill patients on mechanical ventilation. We therefore found ourselves unable to make a reasonable estimation of differences between pulmonary artery pressure measured from bedside echocardiography and pulmonary artery catheter and to perform a power analysis before starting the study. Therefore, as recommended,[16] consecutive patients were included, and the amount of statistical uncertainty was assessed by reporting the 95% confidence interval.

The ability to determine mPAP or its variation from Doppler study of pulmonary artery flow was tested by correlating echocardiographic indices of pulmonary artery flow to mPAP and PVRI, measured and calculated from the pulmonary artery catheter. Using linear regression analysis, the following Doppler variables or calculated indices were correlated to mPAP and PVRI: pET/AT, pET/ED, AT/ED, pET/ED, preejection time divided by square root of the time interval of R wave of electrocardiogram (pET/$\sqrt{}$RR), and AT/$\sqrt{}$RR.[3]

The ability to determine sPAP from Doppler study of tricuspid regurgitation flow was tested by comparing sPAP obtained from the pulmonary artery catheter or its variations induced by nitric oxide inhalation, with estimated sPAP or its variations from peak velocity of tricuspid regurgitation using linear regression analysis and the Bland-Altmann method.[17]

The diagnostic performance of right ventricle enlargement and septal dyskinesia for diagnosing sPAP of 35 mmHg or greater was assessed by calculating sensitivity (true positives/[true positives + false negatives]), specificity (true negatives/[true negatives + false positives]), positive predictive value (true positives/[true positives + false positives]), and negative predictive value (true negatives/[true negatives + false negatives]).

Statistical analysis was performed using NCSS 2004 software (NCSS; Statistical & Power Analysis Software, Kaysville, UT), and the statistical significance level was fixed at 0.05.

Results

Clinical and Echocardiographic Characteristics

The characteristics of the patients are summarized in table 1. According to the criteria proposed by the American-European Consensus Conference,[18] 29 patients had an early stage of acute respiratory distress syndrome, and 16 had an early stage of acute lung injury. Six had a

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Table 1. Clinical and Hemodynamic Characteristics of the Patients

Clinical characteristics	
Age, yr	54 ± 19
Sex ratio, M/F	42/9
Outcome, D/S	10/41
SAPS II	42 ± 14 (16–71)
Cause of admission	
Vascular surgery	24
Abdominal surgery	6
Neurosurgery	3
Medical	2
Multiple trauma	16
Pulmonary characteristics	
LISS	2.2 ± 0.5
ARDS/ALI/pulmonary edema	
n	29/16/6
%	57/31/12
Pa_{O_2}/F_{IO_2}	216 ± 79
Hemodynamic characteristics	
Heart rate, beats/min	90 ± 20 (53–140)
Mean PAP, mmHg	28 ± 6 (16–44)
Systolic PAP, mmHg	39 ± 8 (25–67)
Diastolic PAP, mmHg	21 ± 5 (10–34)
RAP, mmHg	10 ± 5 (1–20)
PCWP	13 ± 5 (2–22)
Cardiac index, $l \cdot min^{-1} \cdot m^{-2}$	3.7 ± 1.1 (1.7–5.9)
Shock, %	90
Septic shock, %	73
Septic and cardiogenic shock, %	17

Data are presented as mean ± SD. Range values in parentheses. n = 51 patients total.

ALI = acute lung injury; ARDS = acute respiratory distress syndrome; D = dead; F_{IO_2} = fraction of inspired oxygen; LISS = Lung Injury Severity Score; Pa_{O_2} = arterial oxygen tension; PAP = pulmonary arterial pressure; PCWP = pulmonary capillary wedge pressure; RAP = right atrial pressure; S = survivor; SAPS = Severity Acute Physiologic Score.

pulmonary edema resulting from left ventricular failure defined as pulmonary capillary wedge pressure greater than 18 mmHg and left ventricular ejection fraction less than 50%. Most of the patients had undergone major surgical procedures and were in circulatory shock, mainly of septic origin. The overall mortality rate was 20%.

Echocardiographic characteristics of the patients are summarized in table 2. Right ventricular dilatation was present in almost half of the patients, whereas acute cor pulmonale was observed in 18% of the patients.

Pulmonary Artery Flow and Mean Pulmonary Artery Pressure

Statistically significant correlations were found between echocardiographic indices characterizing pulmonary artery blood flow and mPAP and PVRI (table 3 and fig. 2) and between variations of these echocardiographic indices and variations of mPAP and PVRI induced by nitric oxide inhalation (table 4). The large 95% confidence intervals, however, suggest that measurement of echocardiographic indices derived from pulmonary artery blood flow did not result in a precise estimate

Table 2. Echocardiographic and Doppler Characteristics of the Patients

Left ventricular function	
$LVEDA_{TG}$, cm^2/m^2	10 ± 2 (5–16)
FAC, %	52 ± 12 (24–70)
VTI ao, cm	16 ± 5 (9–30)
Right ventricular function	
RVEDA/LVEDA, %	65 ± 23 (34–130)
RVEDA/LVEDA > 0.6	25 (49%)
RVEDA/LVEDA >1	4 (8%)
Patients with acute cor pulmonale	9 (18%)
VTI pa, cm	12 ± 4 (5–22)
Vmax, cm/s	89 ± 23 (52–171)

Data are presented as mean ± SD. Range values in parentheses. n = 51 patients total.

FAC = fractional area change; LVEDA = left ventricular end-diastolic area from the four chamber view; $LVEDA_{TG}$ = indexed left ventricular end-diastolic area measured from the transgastric view; RVEDA = right ventricular end-diastolic area from the four chamber view; Vmax = peak velocity; VTI ao = aortic velocity time integral; VTI pa = velocity time integral of pulmonary artery flow.

of mPAP, although they may also result from the relatively small sample size.

Tricuspid Regurgitation and Systolic Pulmonary Artery Pressure

Among the 20 patients in whom transesophageal echocardiography was performed immediately after pulmonary artery catheter removal, tricuspid regurgitation flow was present in 19. Doppler measurement of tricuspid flow was possible in 17 patients (85%), either by transesophageal (59% of the patients) or transthoracic approach (70% of the patients). As shown in figures 3A and B, statistically significant correlations were found between absolute values or variations of sPAP derived from tricuspid regurgitation flow and corresponding values measured by the pulmonary artery catheter. As shown in figures 3C and D, sPAP and its variations could be accurately estimated using Doppler study of tricuspid regurgitation, and the bias of the measurements was quite low.

Value of Right Ventricle Dimensions and Kinetics

As shown in table 5, right ventricle enlargement was poorly predictive of pulmonary artery hypertension. Presence of septal dyskinesia and acute cor pulmonale, although poorly sensitive, was highly specific for detecting pulmonary artery hypertension and had a positive predictive value greater than 0.9 in diagnosing sPAP of 35 mmHg or greater.

Discussion

This study demonstrates that sPAP can be accurately determined from the echocardiographic analysis of tricuspid regurgitation flow in a majority of hypoxemic critically ill patients. mPAP, however, cannot be accu-

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Table 3. Correlations Coefficients (*r* and 95% Confidence Intervals) between Pulmonary Arterial Blood Flow Indices and Mean Pulmonary Arterial Pressure and Indexed Pulmonary Vascular Resistance

Echocardiographic Indices	AT	AT/ED	AT/√RR	pET	pET/ED	pET/√RR	pET/AT
mPAP	−0.10 (−0.38 to 0.19)	−0.15 (−0.43 to 0.16)	−0.13 (−0.43 to 0.21)	0.29* (0.001 to 0.53)	0.26 (−0.04 to 0.51)	0.26 (−0.04 to 0.51)	0.18 (−0.14 to 0.46)
PVRI	−0.35* (−0.59 to 0.01)	0.03 (−0.35 to 0.31)	0.32 (−0.59 to 0.04)	0.24 (−0.08 to 0.52)	0.36* (0.04 to 0.61)	0.27 (−0.06 to 0.54)	0.04 (−0.38 to 0.30)

n = 51 patients total.

* $P < 0.05$.

AT = acceleration time; ED = ejection duration; mPAP = mean pulmonary arterial pressure; pET = preejection time; PVRI = pulmonary vascular resistance index; RR = time interval of R wave of electrocardiogram.

rately inferred from echocardiographic analysis of pulmonary artery flow, in contrast to observations made in spontaneously breathing cardiac patients.

Consequences of Pulmonary Artery Hypertension on Right Ventricular Function

In the critically ill, many clinical situations may lead to pulmonary artery hypertension, the impact of which on right ventricle function is difficult to predict. In fact, echocardiography is indispensable for diagnosing acute cor pulmonale, an early and accurate sign of pulmonary hypertension–induced right ventricle overload. Apart from this typical situation, pulmonary hypertension is ignored if not measured by right heart catheterization. Because of its complex crescent-shape structure wrapped around the left ventricle, estimation of right ventricular volume is not easy. Faced to an acute increase in afterload, as observed in acute respiratory distress syndrome, the right ventricle has no time to hypertrophy and dilates. Using echocardiography, right ventricular dimensions can be indirectly estimated by measuring right-to-left ventricular end-diastolic area ratio. In critically ill hypoxemic patients, right ventricular dilatation most often results from a mismatch between the right ventricle and its afterload. As a consequence, evaluation of right ventricular function to be complete should include estimation of right ventricular pressure, *i.e.*, pulmonary artery pressure. For the clinician, the possibility of measuring pulmonary artery hypertension accurately by echocardiography is therefore of clinical importance.

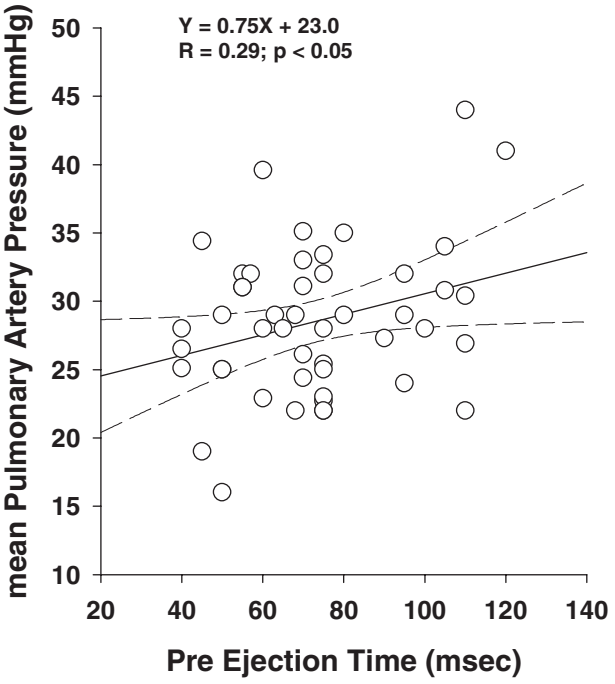

Fig. 2. Correlation existing between preejection time and mean pulmonary artery pressure measured by right heart catheterization (RHC mPAP) in 50 patients. Individual values of preejection time are plotted against RHC mPAP. A significant correlation exists between preejection time and RHC mPAP.

Estimation of Pulmonary Artery Pressure from Doppler Study of Pulmonary Artery Flow

In cardiac patients, Doppler examination of pulmonary artery flow at the main trunk of pulmonary artery is accurate for diagnosing pulmonary artery hypertension.[1–3] The normal pulmonary artery flow shape is rounded, with a peak velocity of 60–100 cm/s occurring at the middle of the ejection and an acceleration time to duration ejection ratio of 50%. When right ventricular afterload increases under the influence of pulmonary artery hypertension, the pulmonary artery flow becomes steeper. The ejection and acceleration times, and especially their ratio to ejection duration, decrease. On the contrary, the pET is increased. In case of severe right ventricular overloading, a "mesosystolic fall" can occur, rendering the pulmonary artery flow biphasic (fig. 4). In the mid-1980s, two studies found that such a pulmonary flow pattern had a high specificity for detecting pulmonary artery hypertension in cardiac patients.[1,19] Further studies performed in cardiac patients found a good correlation between Doppler indices characterizing pulmonary artery flow and mPAP or PVRI. Correlations improved when correction for heart rate was made by dividing acceleration time by right ventricular ejection time.[2,20,21] Using the transthoracic approach, alignment with pulmonary artery may be difficult, rendering the pulmonary flow analysis imprecise, especially for acceleration time and duration of ejection.[22]

In ventilated critically ill patients, the transthoracic examination may even be more difficult, and the transesophageal route may offer an alternative. To our knowl-

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Table 4. Correlations Coefficients (*r* and 95% Confidence Intervals) between Variations of Different Pulmonary Arterial Flow Indices and Variations of Mean Pulmonary Arterial Pressure and Pulmonary Vascular Resistance Induced by Nitric Oxide Inhalation

Variations of Echocardiographic indices	ΔAT	ΔAT/ED	ΔAT/√RR	ΔpET	ΔpET/ED	ΔpET/√RR	ΔpET/AT
ΔmPAP	0.40* (0.08/0.63)	0.37* (0.04/0.62)	0.38* (0.02/0.63)	−0.15 (−0.43/0.17)	−0.04 (−0.39/0.28)	0.32 (−0.001/0.57)	−0.15 (−0.45/0.18)
ΔPVRI	0.62‡ (0.35/0.79)	0.46† (0.12/0.69)	0.37* (0.02/0.63)	−0.08 (−0.40/0.25)	−0.16 (−0.47/0.18)	0.10 (−0.24/0.41)	−0.04 (−0.39/0.29)

n = 41 patients total.

* $P < 0.05$. † $P < 0.01$. ‡ $P < 0.0001$.

ΔAT/√RR= variation of acceleration time divided by square root of time interval of R wave of electrocardiogram; ΔED = variation of ejection duration; ΔmPAP = variation of mean pulmonary arterial pressure; ΔpET = variation of preejection time; ΔPVRI = variation of pulmonary vascular resistance index.

edge, only a single study reported the use of transesophageal echocardiography for estimating mPAP in postoperative mechanically ventilated patients. Surprisingly, an accurate estimation of mPAP was possible from Doppler study of the pulmonary artery flow only before sternotomy.[3] No evaluation has been performed in critically ill patients with pulmonary artery hypertension. Our patients had increased mPAP (29 ± 6 mmHg; range, 16–44 mmHg) and PVRI, mainly related to acute lung injury and acute respiratory distress syndrome. As a consequence, the pulmonary artery flow was in most patients steeper than normal, with an AT/ED of 37 ± 12.

As expected, inhalation of nitric oxide induced a significant decrease in right ventricle afterload and affected the morphology of the right ventricular flow and, thereby, the pulmonary artery flow. Inhalation of nitric oxide facilitated right ventricular ejection and induced an increase in ejection duration and acceleration time and a reduction of pET with a significant decrease in pET/ED. However, because it did not completely reverse pulmonary artery hypertension, pulmonary artery flow remained steeper with a reduced AT/ED. The decrease in pET and its derived indices was statistically significant, but correlations with mPAP and PVRI or their nitric oxide–induced variations remained weak and clinically irrelevant.

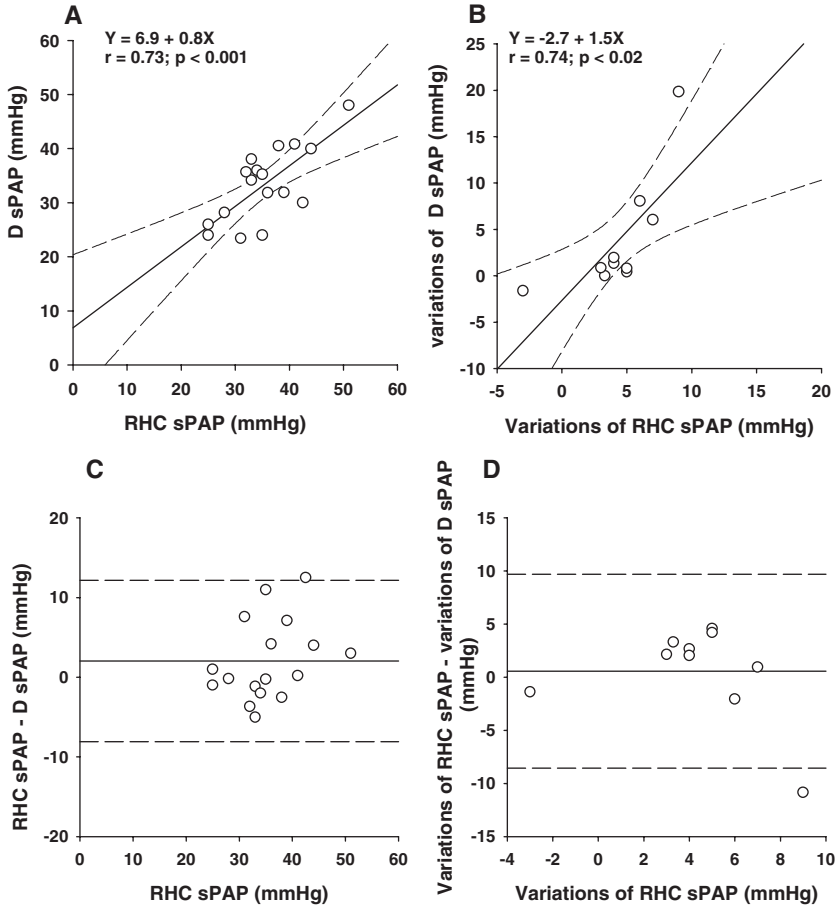

Fig. 3. (*A*) Correlation existing between systolic pulmonary artery pressure measured by right heart catheterization (RHC sPAP) and sPAP estimated from Doppler study of tricuspid regurgitation (D sPAP) in 17 patients. Individual values of D sPAP are plotted against RHC sPAP. A significant correlation exists between RHC sPAP and D sPAP. (*B*) Correlation existing between variations of RHC sPAP and variations of sPAP estimated from D sPAP in 10 patients. Individual values of variations of D sPAP are plotted against variations of RHC sPAP. A significant correlation exists between variations of RHC sPAP and variations of D sPAP. (*C*) Bias and precision of D sPAP in 17 patients. The mean bias was 2.0 mmHg. The *dotted lines* represent 2 SDs (precision of the bias, according to the Bland-Altman method). (*D*) Bias and precision of variations of D sPAP in 10 patients. The mean bias was 0.6 mmHg. The *dotted lines* represent 2 SDs (precision of the bias, according to the Bland-Altman method).

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Table 5. Specificity, Sensitivity, and Positive and Negative Predictive Values of Echocardiography Findings for Diagnosing Pulmonary Artery Hypertension

	Systolic Pulmonary Artery Pressure ≥35 mmHg			
	Sp	Se	PPV	NPV
Right ventricle enlargement	0.56	0.51	0.72	0.35
Septal dyskinesia	0.94	0.26	0.90	0.39
Acute cor pulmonale	0.94	0.21	0.88	0.37

Right ventricle enlargement is defined by a ratio right ventricular end-diastolic area/left ventricular dilatation greater than 60%. Septal dyskinesia was defined by septal flattening or paradoxical septal motion. Acute cor pulmonale was defined by the association of a septal dyskinesia with a right ventricle enlargement.

NPV = negative predictive value; PPV = positive predictive value; Se = sensibility; Sp = specificity.

Many factors may explain the absence of tight correlation between mPAP and Doppler indices of pulmonary artery blood flow. In fact, pulmonary artery flow waveform depends on right ventricular preload, right ventricular systolic contractility, pulmonary vascular resistances, and the interplay between them. This study was conducted in a majority of critically ill patients with septic shock, whose loading conditions and cardiac contractility, the main factors that influence pulmonary artery flow waveform, are essentially variable and prone to change. In the current study, right ventricular function varied from normal to acute cor pulmonale. Right ventricular dilatation was present in half of the patients, often resulting from mechanical ventilation with positive end-expiratory pressure. Left cardiac function varied from normal to severely impaired left ejection fraction. Echocardiographic parameters indirectly reflecting preload, such as left ventricular end-diastolic area, pulmonary capillary wedge pressure, right ventricular end-diastolic area, and right atrial pressure, demonstrated a wide dispersion, attesting of the heterogeneity of loading conditions among patients. Two additional confounding factors, by interfering with pulmonary artery flow waveform, likely contributed to the weak correlations existing between indices of pulmonary artery flow and pulmonary artery pressure: the administration of catecholamines to 90% of patients and the effects of mechanical ventilation.

Estimation of Pulmonary Artery Pressure from Doppler Study of Regurgitation Tricuspid Flow in Critically Ill and Ventilated Patients

Measurement of sPAP from the Doppler analysis of tricuspid regurgitation flow relies on the application of the simplified Bernouilli equation, stating that instantaneous right ventricular to right atrial pressures gradient determines velocity of tricuspid regurgitation.[5] Several potential errors should be taken into account before considering Doppler-determined gradients as accurate. First, the assumption that the beam-to-flow angle is negligible may be wrong. In ventilated patients undergoing transesophageal echocardiography, difficulty in alignment with tricuspid regurgitation can be encountered. If the angle exceeds 20°, the peak velocity of tricuspid regurgitation is significantly underestimated and the pressure gradient even more, because velocity is squared.[23] Second, if right atrial pressure is estimated from jugular pressure or size of inferior vena cava, it can differ from the actual right atrial pressure at the time of peak transtricuspid flow. In our study, right atrial pressure was measured directly from the central venous line to avoid such a bias. A third source of potential error is the time elapsed between invasive and Doppler echocardiographic measurements of pulmonary artery pressure. In critically ill patients with shock and varying loading conditions, two periods of measurements far apart in time may result in discrepancies. In addition, the presence of a pulmonary artery catheter within right cardiac

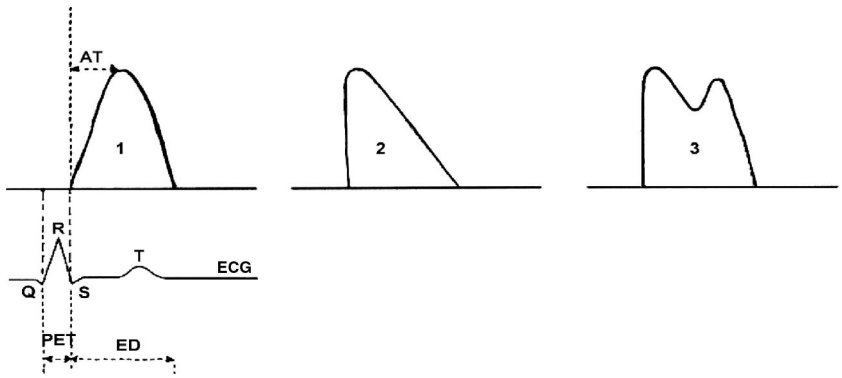

Fig. 4. Doppler examination of pulmonary artery flow at midesophageal ascending aortic short axis view. (*1*) Normal pulmonary artery flow shapely rounded with a peak velocity of 60–100 cm/s occurring at the middle of the ejection with an acceleration time to duration ejection ratio of 50%. (*2*) Moderate pulmonary artery hypertension. The pulmonary artery flow becomes steeper. The acceleration times, and especially its ratio to ejection duration, decrease. The preejection time is increased. (*3*) Biphasic pulmonary artery flow during severe right ventricular overloading with a "mesosystolic fall." AT = acceleration time (time interval between onset and peak of pulmonary artery flow velocity); ECG = QRS complex and T waves; ED = ejection duration; pET = preejection time (time interval from onset of electrocardiographic Q wave to initial systolic upward deflection of pulmonary artery flow).

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cavities induces or increases tricuspid regurgitation, which tends to overestimate peak velocity of tricuspid regurgitation and may complicate alignment with tricuspid flow regurgitation. As a consequence, the Doppler study of tricuspid regurgitation for estimating sPAP must be performed in the few minutes after pulmonary artery measurement and withdrawal of the pulmonary artery catheter, as in the current study.

Potential Benefit of Noninvasive Assessment of Pulmonary Artery Pressures

The pulmonary artery catheter remains the accepted standard for measuring pulmonary artery pressure. The insertion of a pulmonary artery catheter is, however, associated with potential adverse effects and complications, including death.[24] In addition, many randomized studies have failed to demonstrate that the insertion of a pulmonary artery catheter improves survival,[25] whereas a few nonrandomized studies have suggested an increased morbidity and mortality. Therefore, the risk–benefit ratio of the pulmonary artery catheter remains uncertain. As a consequence, any noninvasive method providing an accurate assessment of cardiac filling pressures at the bedside seems to be an attractive alternative in critically ill patients.

Conclusion

In critically ill hypoxemic patients on mechanical ventilation, mPAP cannot be reliably estimated from transesophageal echocardiographic indices characterizing pulmonary artery blood flow. In the majority of patients, however, sPAP can be estimated from the Doppler study of regurgitation tricuspid flow using either a transthoracic or a transesophageal approach.

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