The Right Ventricle During the Acute Respiratory Distress Syndrome Revisited by Echocardiography

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Abstract: We illustrate the valuable information provided by echocardiography for hemodynamic monitoring and for optimizing ventilatory strategies, during ARDS. Although the transthoracic and the transesophageal routes can be used, we always prefer, in the absence of contraindications, to perform transesophageal echocardiography.

ARDS includes numerous affections which brutally damage the interface between the distal airway tract and pulmonary vascular bed. Two factors combine to produce right ventricular systolic overload, the pathologic features of the syndrome per se and mechanical ventilation.

Acute cor pulmonale (ACP) reflects the severity of the pulmonary disease, but may also be caused or exacerbated by an aggressive and unsuitable ventilatory strategy. With tidal volume limitation, the incidence of ACP has declined to 25%. Providing that ventilatory management is adapted to right ventricular function, ACP is no longer significantly associated with increased mortality. If not, it is demonstrated that right ventricular dysfunction is actually associated with a poor prognosis.

In conclusion, whereas some have promoted a lung protective approach, echocardiography allows us to promote a right ventricular protective approach, by adapting respiratory settings to right ventricular function, which is key in the prognosis of these patients.

Keywords: ARDS, hemodynamics, right ventricle, echocardiography.

INTRODUCTION

In recent years, bedside use of Doppler echocardiography has supplanted invasive procedures in assessing cardiac function in critically ill patients. Pulmonary artery catheterization, an invasive procedure, gives indirect information related to right-sided heart function. This technique was gradually compromised, the measures being of debatable reliability in mechanical ventilation [1]. A qualitative and repetitive echocardiographic evaluation, by a simple visualization in real time of the kinetics and size of cardiac cavities, has been shown to be essential in assessing right-sided heart afterloading [2]. In addition, it should be considered that right ventricular dysfunction may affect left ventricular function, not only by limiting left ventricular preload, but also by adverse systolic and diastolic interactions *via* the intraventricular septum and the pericardium (ventricular interdependence). An experienced critical care intensivist with a sufficient echocardiographic background can immediately establish a functional diagnosis and aid clinical decision-making. In this clinical review we illustrate the valuable information provided by echocardiography for hemodynamic monitoring and for optimizing ventilatory strategies, during ARDS, a situation well known to be associated with pulmonary hypertension and right heart dysfunction.

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PHYSIOLOGY AND PATHOPHYSIOLOGY

Systolic function of the right ventricle may be represented by the coupling between "intrinsic" contractility of the right ventricle and its afterload [3]. In physiologic conditions, contractility is somewhat secondary, because simple negative pleural pressure produced by breathing promotes blood flow through the pulmonary circulation and ensures sufficient pulmonary venous return. The right ventricle acts as a passive conduit. This is possible because the right ventricle ejects blood into a low-resistance, high-compliance circuit. The volume of blood present in the pulmonary circulation is the filling reserve of the left ventricle. A reduction in this volume immediately affects the left ventricular preload and may cause decreased left ventricular stroke volume and finally circulatory failure.

Conversely, in pathologic conditions in which there is some increase in pulmonary vascular resistance, "intrinsic" contractility becomes essential to maintain an optimal coupling between the right ventricle and the pulmonary circulation and then to promote pulmonary blood flow. Unfortunately, unlike the left ventricle, adaptation of the

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right ventricle is limited. It can be argued that right ventricular systolic function is sensitive: even a slight increase in pulmonary vascular resistance can overload a normal right ventricle, thereby impairing its systolic function. In response, because of a significantly low diastolic elastance, the right ventricle dilates acutely [4]. It can be argued that right ventricular diastolic function is tolerant.

ARDS includes numerous affections which brutally damage the interface between the distal airway tract and pulmonary vascular be d. Two factors combine to produce right ventricular systolic overload. The first regards the pathologic features of the syndrome per se, which is associated with distal occlusion of the pulmonary arterial bed [5] and with pulmonary vascular remodeling (muscularization of usually non-muscularized arteries) mediated by hypoxia and hypercapnia (Fig. **1**). The second factor is mechanical ventilation, which increases right ventricular outflow impedance because of the elevated transpulmonary pressure due to lung compliance impairment [6,7]. Increasing tidal volume increases right ventricular afterload during tidal ventilation, whereas increasing PEEP induces increased afterload during both tidal ventilation and expiration (Fig. **2**) [8]. When right ventricular afterload is progressively increased, the related prolonged right ventricular contraction is responsible for a reversal in the transseptal pressure gradient, especially at end systole [9,10]. This explains why paradoxical septal motion can be observed.

As a consequence, pulmonary hypertension is common in ARDS [11]. In certain situations, it can lead to a pattern of acute cor pulmonale (ACP), defined as the association between right ventricular enlargement, indicative of diastolic overload, and paradoxical septal motion, indicative of systolic overload (Fig. **3**) [12]. The echocardiographic pattern of ACP complicating ARDS was first described in 1985 [13].

ECHOCARDIOGRAPHIC EXAMINATION IN ARDS

Although the transthoracic and the transesophageal routes can be used, we always prefer, in the absence of contraindications, to perform transesophageal echocardiography. In these mechanically ventilated patients, it is safe, minimally invasive and allows good reproducibility of the evaluation, whoever the operator, at different periods of time.

Echocardiographic examination of the right ventricle requires a long-axis view of the heart to evaluate the size of the cavity and a short-axis view to evaluate the septal kinetics. The examination can be completed by Doppler examination of the right ventricular ejection flow and of the backward flow across the tricuspid valve when present.

Right Ventricular Size Assessment

Right ventricular diastolic dimensions can be obtained by measuring right ventricular end-diastolic area in a long-axis view obtained by a transthoracic or transesophageal route (Fig. **3**). The best way to quantify right ventricular dilatation is to measure the ratio between the right and left ventricular end-diastolic areas, which circumvents individual variation

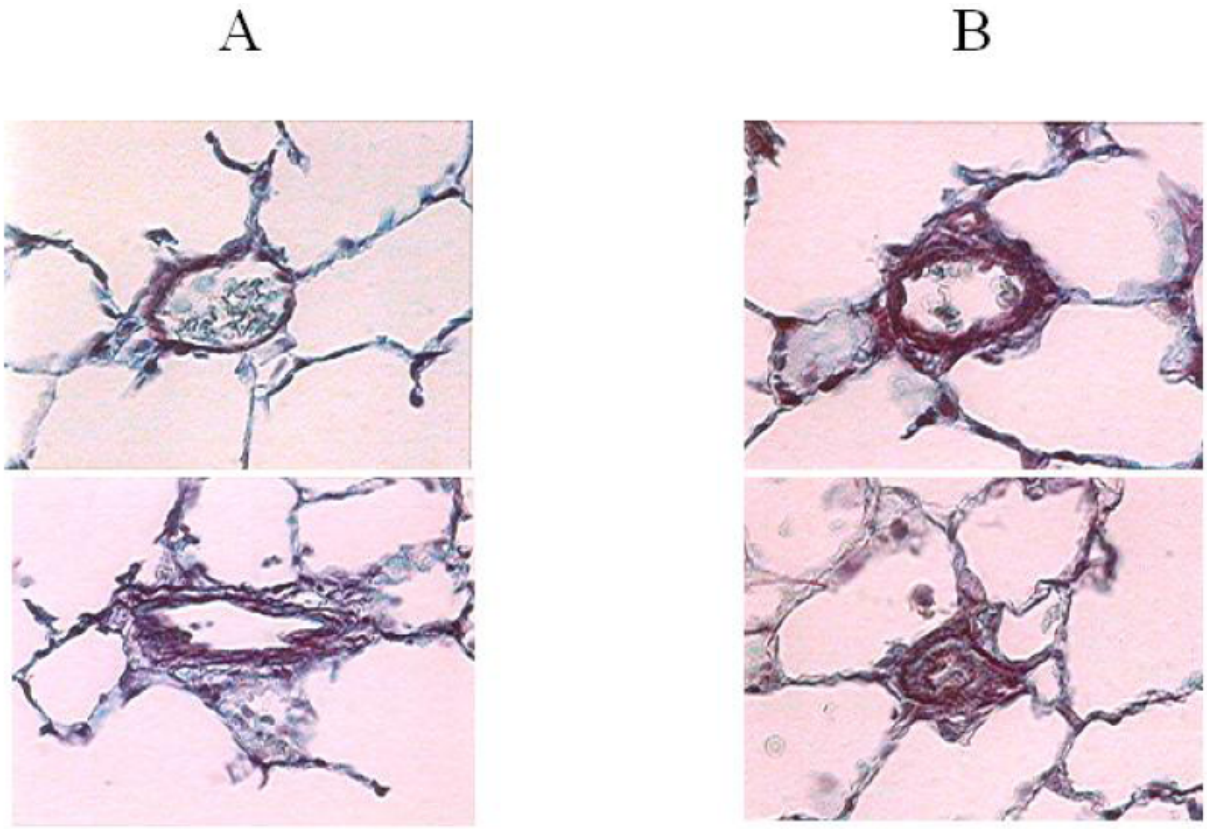

Fig. (1). Lung sections in a rat exposed to 21% oxygen (panel **A**) and in a rat exposed to 10% oxygen for 10 days (panel **B**). Whereas in rat A, pulmonary arteries were normally non-muscularized, pulmonary vascular remodeling occurred in rat B.

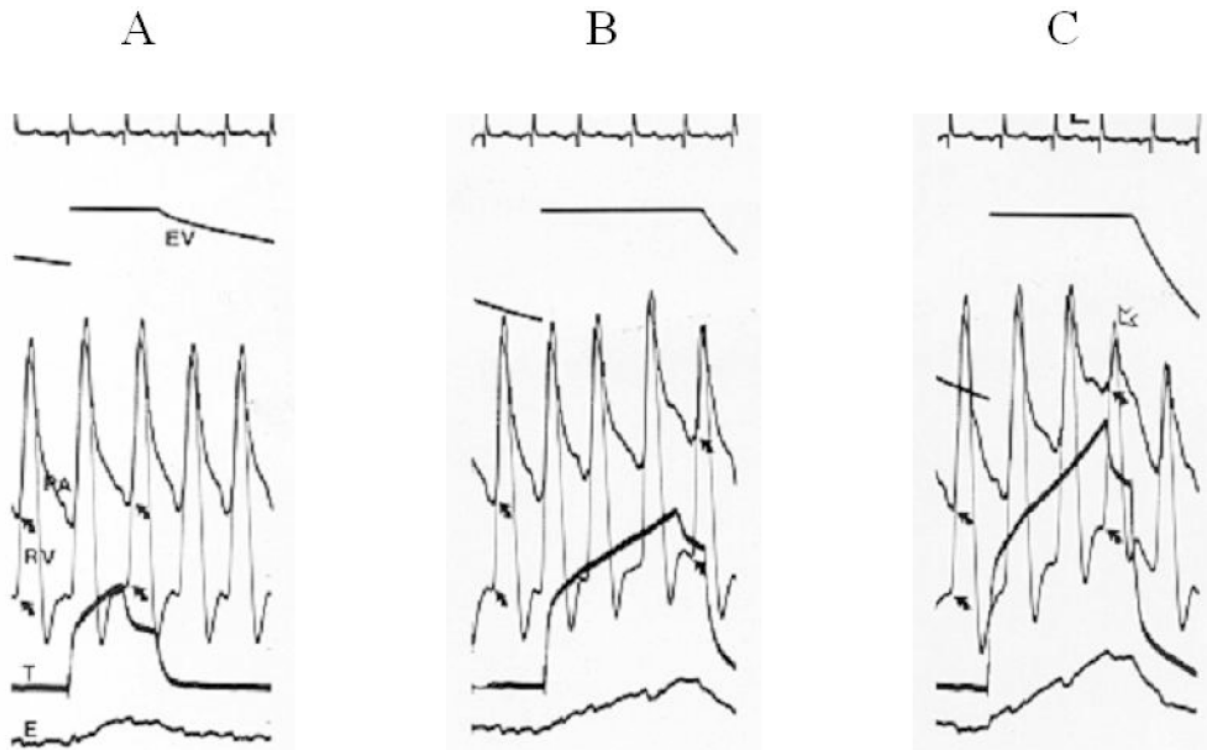

Fig. (2). Right heart catheterization in a patient mechanically ventilated for ARDS during an increase in tidal volume from a low level (panel **A**) to a high level (panel **C**). Increasing tidal volume was responsible during insufflation for an increase in the isovolumetric contraction pressure (arrows) and for a decrease in pulmonary pulse. The two reflect a decrease in right ventricular stroke volume related to increased afterload. T: tracheal pressure, E: esophageal pressure, RV: right ventricular pressure, PA: pulmonary artery pressure.

in cardiac size. In a group of normal volunteers, we reported a mean normal ratio of 0.48 ± 0.12 [14]. We have thus defined moderate right ventricular dilatation as a ratio greater than 0.6 and major right ventricular dilatation as a ratio greater than or equal to 1 [12]. However, gradation of right ventricular dilatation by ventricular diastolic area ratio may be inoperative when chronic left ventricular dilatation is present, because of valvular disease or dilated cardiomyopathy.

Septal Dyskinesia

Paradoxical septal motion is best observed in a short-axis view recorded by either a parasternal or transgastric approach (Fig. **3**). When present at end-systole, it reflects systolic overload of the right ventricle, as emphasized above. Most of the time, the evaluation of septal kinetics is qualitative, but the systolic eccentricity index has been proposed to "quantify" the systolic overload of the right ventricle [15]. A value close to 1 is normal, whereas a value higher than 1 reflects systolic overload of the right ventricle.

Pulmonary Arterial Hypertension

Pulmonary hypertension is usually associated with tricuspid regurgitation. Measurement of the maximal velocity of tricuspid backward flow with continuous wave Doppler allows estimation of systolic pulmonary artery pressure. A moderate elevation is usually observed, but the value should be viewed with caution because systolic pulmonary artery pressure also depends on right ventricular systolic fuction. In fact, in some extreme acute cor pulmonale, pulmonary hypertension may be lacking because major right ventricular failure with inefficient right ventricular contraction is responsible for markedly low cardiac output [16].

Interestingly, we have demonstrated in ARDS that the right ventricle is able in only a few days to thicken in response to an increase in pulmonary pressure. We described a moderate thickness of the right ventricular free wall after 2 days of mechanical ventilation [2].

Doppler examination of pulmonary artery flow velocity can reveal alterations of the flow due to acute pulmonary hypertension: a decrease in the velocity time integral, reflecting the decrease in right ventricular stroke volume, a reduction in acceleration time and sometimes a biphasic flow pattern (Fig. **4**). Moreover, when pressure in the right atrium exceeds that in the left atrium, the foramen ovale may open. The detection of a patent foramen ovale requires contrast echocardiography and has been greatly improved by transesophageal echocardiography [17]. It can be also diagnosed using color-flow Doppler echocardiography.

Left Ventricular Consequences of Acute Cor Pulmonale

Sudden right ventricular enlargement in the stiff pericardial space causes left ventricular compression (Fig. **4**). In consequence, the normal left ventricular end-diastolic volume is decreased in acute cor pulmonale [18]. Left ventricular filling impairment in acute cor pulmonale results from combined pulmonary vascular occlusion and septal displacement [19]. This acute preload deficit often produces or precipitates acute circulatory failure in this setting [18].

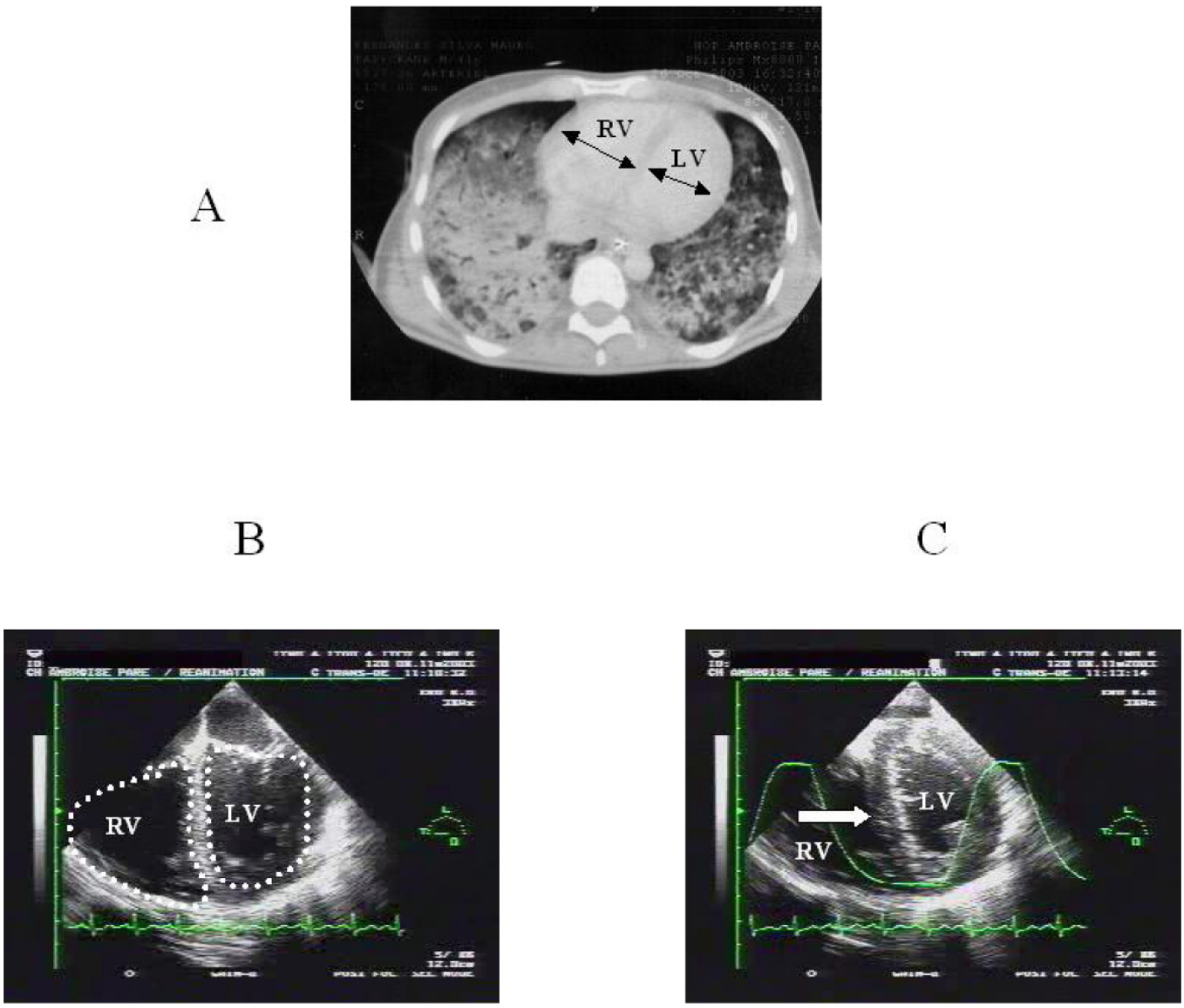

Fig. (3). Patient mechanically ventilated for severe ARDS. CT scan (panel **A**) showed severe bilateral lung injury, but also right ventricular dilatation. Transesophageal echocardiography demonstrated a pattern of acute cor pulmonale with dilatation of the right ventricle (panel **B**) and paradoxical septal motion in systole (panel **C**, arrow). RV: right ventricle, LV: left ventricle.

The latter produces abnormal left ventricular relaxation, which is also evidenced by an abnormal mitral profile. The ratio of peak velocity during early diastolic filling (E wave) to peak velocity of the atrial systole (A wave) is inverted in acute cor pulmonale complicating acute respiratory distress syndrome [18].

WHY PROTECT THE RIGHT VENTRICLE IN PATIENTS WITH ARDS, AND HOW?

When high tidal volumes were used (13 mL/kg), the incidence of ACP was high (61%) and this was associated with a poor prognosis [13]. In the most severe forms, with a right ventricle bigger than the left ventricle, we have even observed 100% mortality [13]. More recently, with tidal volume limitation, the incidence of ACP in acute respiratory distress syndrome has declined to 25% [18]. Providing that ventilatory management is adapted to right ventricular function, ACP is no longer significantly associated with increased mortality. If not, it is clearly demonstrated that right ventricular dysfunction is actually associated with a poor prognosis. We showed that mortality was not different in patients with or without ACP providing that the plateau pressure is maintained below 27 cmH_2O, whereas there was a significant difference when plateau pressure was higher than 27 cmH_2O [20]. This was confirmed by Osman *et al*. who reported in a large series that right ventricular dysfunction was an independent parameter of mortality if ventilatory settings are not adapted [21]. So, many arguments underscore the need to adapt mechanical ventilation to right ventricular function. Observation of ACP may thus lead to suppression or limitation of the different factors known to favor right ventricular systolic overload, i.e. high plateau pressure, high PEEP and hypercapnia. Plateau pressure should be re-examined and maintained below 27 cmH_2O, as explained above. PEEP should also be limited. The mean PEEP in our unit in ARDS is 7 cmH_2O

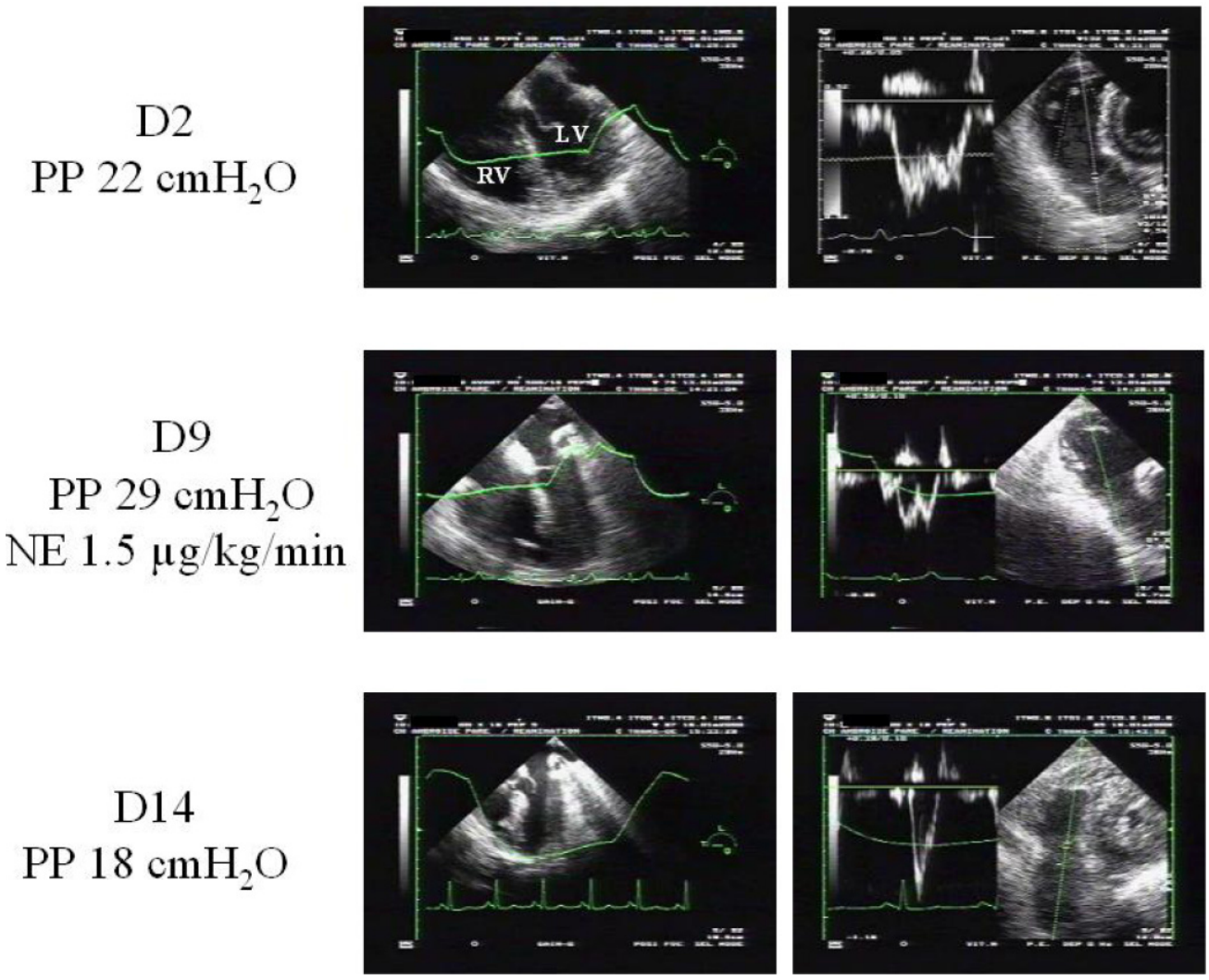

Fig. (4). Evolution of right ventricular function from admission (D2) to recovery (D14) in a patient ventilated because of severe ARDS related to pneumonia. At day 2, plateau pressure was 22 cmH_2O. Hemodynamics were normal. Echocardiography demonstrated moderate dilatation of the right ventricle with an incipient biphasic pattern of the pulmonary flow. The right ventricular stroke volume was conserved. At day 9, following major deterioration in respiratory mechanics (plateau pressure 29 cmH_2O), echocardiography demonstrated major dilatation of the right ventricle leading to strong restriction of the left ventricle. The pulmonary flow showed a clear biphasic pattern with a decrease in right ventricular stroke volume. The patient was in shock and required high-dose norepinephrine infusion. Finally, at day 14, after recovery of lung function, right ventricular function appeared normal and hemodynamics also. PP: plateau pressure, NE: norepinephrine, RV: right ventricle, LV: left ventricle.

because we always favor oxygen transport rather than oxygen content [22]. Intrinsic PEEP should absolutely be avoided. It is often caused by an excessive respiratory rate, an insidious cause of right ventricular afterloading [23]. Because $PaCO_2$ is a well-known factor which promotes pulmonary hypertension, the presence of ACP may induce limitation of the hypercapnia. We recently reported very poor tolerance in terms of right ventricular function in ARDS patients subject to significant hypercapnia [24]. Hypercapnia must be limited first by increasing the respiratory rate, without inducing intrinsic PEEP, and second by removing the heat moisture exchanger and using instead a heated humidifier [25]. If PEEP reduction does not appear possible in the supine position without worsening hypoxemia, prone positioning should be considered on day 3. We demonstrated that this positioning strategy in the most severely ill patients, i.e. patients with a persistent P/F ratio below 100 mmHg after 2 days of mechanical ventilation, was responsible for a dramatic improvement in oxygenation and in respiratory mechanics [26]. Interestingly, we reported that it was also good for the right ventricle, by unloading it [27].

Finally, in a very few situations, after adapting respiratory settings to right ventricular function, NO inhalation can be tested in patients with persistent shock related to ACP.

CONCLUSION

In conclusion, in ARDS, acute cor pulmonale reflects the severity of the pulmonary disease involving the microvasculature, but may also be caused or exacerbated by an aggressive and unsuitable ventilatory strategy. The classic clinical description of acute cor pulmonale has to be revised

and completed by a more modern approach based on echocardiographic changes in the size and function of the heart. These echocardiographic findings allow us to assess the hemodynamic consequences and prognostic implications of acute respiratory distress syndrome. Whereas some have promoted a lung protective approach, especially based on high PEEP, echocardiography allows us to promote a right ventricular protective approach, by adapting respiratory settings to right ventricular function, which is key in the prognosis of these patients.

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