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Influence of Respiratory Rate on Stroke Volume Variation in Mechanically Ventilated Patients

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Background: **Heart-lung interactions are used to evaluate fluid responsiveness in mechanically ventilated patients, but these indices may be influenced by ventilatory conditions. The authors evaluated the impact of respiratory rate (RR) on indices of fluid responsiveness in mechanically ventilated patients, hypothesizing that pulse pressure variation and respiratory variation in aortic flow would decrease at high RRs.**

Methods: **In 17 hypovolemic patients, thermodilution cardiac output and indices of fluid responsiveness were measured at a low RR (14–16 breaths/min) and at the highest RR (30 or 40 breaths/min) achievable without altering tidal volume or inspiratory/expiratory ratio.**

Results: **An increase in RR was accompanied by a decrease in pulse pressure variation from 21% (18–31%) to 4% (0–6%) ($P < 0.01$) and in respiratory variation in aortic flow from 23% (18–28%) to 6% (5–8%) ($P < 0.01$), whereas respiratory variations in superior vena cava diameter (caval index) were unaltered, *i.e.*, from 38% (27–43%) to 32% (22–39%), P = not significant. Cardiac index was not affected by the changes in RR but did increase after fluids. Pulse pressure variation became negligible when the ratio between heart rate and RR decreased below 3.6.**

Conclusions: **Respiratory variations in stroke volume and its derivates are affected by RR, but caval index was unaffected. This suggests that right and left indices of ventricular preload variation are dissociated. At high RRs, the ability to predict the response to fluids of stroke volume variations and its derivate may be limited, whereas caval index can still be used.**

FLUID challenge is commonly performed in critically ill patients, but the response is variable.[1] To improve the prediction of fluid responsiveness, new indices based on respiratory variation in preload have been introduced into clinical practice.[2,3] These indices are generally based on cyclic changes in intrathoracic pressure induced by mechanical ventilation. During insufflation, there is a combined decrease in right ventricular preload and increase in right ventricular afterload, leading to a reduction in the right ventricular stroke volume in patients who are likely to respond to fluid therapy (or in patients with acute cor pulmonale). Simultaneously, there is an increase in left ventricular preload by the purge of pulmonary veins induced by the increase in alveolar pressure, which can increase left ventricular stroke volume in these patients.[4] After a few beats, corresponding to the transit time into the pulmonary vessels, the decreased right ventricular stroke volume induces a decrease in left ventricular preload, leading to a decrease in left ventricular stroke volume in preload-dependent patients. The cyclic changes in ventricular preload induced by mechanical ventilation thus result in concurrent changes in left ventricular stroke volume in preload-dependent but not in preload-independent patients. Dynamic indices of preload can better predict the individual response to fluid loading than static indices such as cardiac filling pressures or end-diastolic volumes.[1,2,5]

However, these indices may be sensitive to ventilatory conditions and to heart rate (HR). In healthy animals breathing spontaneously, Morgan *et al.*[6] reported 40 yr ago that respiratory variations in right and left ventricular stroke volume decreased with tachypnea and tachycardia. This was a general statement, and the authors did not provide a value of HR or respiratory rate (RR) at which these variations disappeared. However, several authors have reported that stroke volume variations or systolic and pulse pressure variations occur in hypovolemic conditions, with HRs varying from 70 to 150 beats/min.[7–10] These observations suggest that HR alone is probably not a limiting factor. RR may be more relevant, and this may be more crucial for critically ill patients who are often ventilated at high RRs either in the context of protective ventilation[11] or to compensate a severe metabolic acidosis.

We propose that the number of cardiac beats per respiratory cycle or the ratio between HR and RR could be more crucial than HR or RR alone. Indeed, an interval of 3 to 4 cardiac beats is usually observed between the highest and lowest left ventricular stroke volume, due to the pulmonary transit time. Pulmonary transit time is dependent on the HR and not the RR. As pulmonary transit time is independent of RR, the time required for transmission of decreased right ventricular stroke volume to the left heart is fixed. As the circulation is pulsatile, this pulmonary transit time requires a few cardiac beats. On the contrary, the increase in left ventricular preload due to the purge effect is dependent on RR and independent of HR. At some point, the combi-

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nation of the increase (purge effect) and decrease (decreased right ventricular output) in left ventricular preload merge, so that respiratory variations in left ventricular preload are abolished. One may expect that if the RR increases, there would be some point at which the number of beats per respiratory cycle, estimated by the HR to RR ratio, would be insufficient to allow stroke volume variation to occur. This effect may, at least partially, contribute to the decreased predictive value of fluid responsiveness during mechanical ventilation at low tidal volumes[12] (when the RR is usually increased to limit the development of hypercapnia) and also during spontaneous ventilation in tachypneic patients.[13]

Respiratory variations in right ventricular output are likely to be preserved because respiratory changes in right ventricular preload and afterload occur simultaneously. Hence, RR would not affect respiratory variations in right ventricular stroke volume provided that at least one cardiac beat occurs in each part of the respiratory cycle. Accordingly, one may expect to have dissociation between respiratory variations in right and left ventricular stroke volumes at high RRs.

We evaluated the effects of RR on various dynamic indices of fluid responsiveness in a series of invasively monitored hypovolemic patients in whom hemodynamic evaluation was performed by transesophageal echocardiography. We hypothesized that respiratory variations in left but not right ventricular stroke volume (and its derivates) would disappear at high RRs.

Materials and Methods

The study was approved by the Ethical Committee of the hospital (Comité d'Ethique Hospitalo-Facultaire ULB-Erasme, Université Libre de Bruxelles, Brussels, Belgium) and informed consent was obtained from the patient or relatives.

Patients

We included patients in circulatory failure (defined as a mean arterial pressure less than 65 mmHg and/or need for vasopressor agents) with a pulse pressure variation (ΔPP, see Measurements below) greater than 10% and who required a transesophageal echocardiographic evaluation to exclude causes of circulatory failure other than hypovolemia. All patients had to be treated with mechanical ventilation with a tidal volume of at least 8 ml/kg.[12]

Exclusion criteria were age less than 18 yr, pregnancy, significant cardiac arrhythmia (atrial fibrillation or numerous premature beats), presence of spontaneous respiratory movements, known aortic or mitral valve diseases or valvular prosthesis, presence of obstructive lung disease, air leakage through chest drains, and signs of expiratory flow limitation as evidenced by the analysis of expiratory flow curves or by the presence of an intrinsic positive end-expiratory pressure (PEEP) higher than the external PEEP.

Protocol

Mechanical ventilation was provided on a volume predetermined mode (Evita 4, Dräeger; Lübeck, Germany; or Servo I, Maquet, Solna, Sweden) with a tidal volume of 8–10 ml/kg (ideal body weight) at an initial RR of 14–16 breaths/min. The patients were already deeply sedated, and nine also received muscle paralysis. No specific alteration in sedation or induction of paralysis was required for the study.

A complete set of measurements was obtained at baseline. Thereafter, for the purpose of the investigation, RR was increased to 30 breaths/min for 5 min and then to 40 breaths/min for another 5 min (when the HR to RR ratio was still greater than 3 at 30 breaths/min). Tidal volume and external PEEP were kept constant, but the inspiratory time was decreased to keep the inspiratory to expiratory time ratio constant. Accordingly, inspiratory flow increased. Hemodynamic and echocardiographic measurements were obtained at RRs of 30 breaths/min and 40 breaths/min. Thereafter, the patient was again placed on the initial ventilatory conditions, and 1,000 ml of a Ringer lactate solution was infused over 20 min. The hemodynamic measurements were repeated at the end of the fluid infusion.

Measurements

Arterial pressure was measured *via* radial or femoral catheters. Cardiac index was measured by semicontinuous thermodilution (pulmonary artery catheter, CCO; Edwards Healthcare, Irvine, CA) on a rapid mode in 13 patients and by pulse contour analysis (PiCCOplus; Pulsion, Munich, Germany) in 4 patients. The latter method was calibrated at baseline by using transpulmonary thermodilution (three bolus injections were averaged). For both methods, eight consecutive measurements were averaged. After calibration, arterial and intravascular pressures were recorded on a computer.[12] Central venous pressure, mean pulmonary artery pressure, pulmonary artery occluded pressure and mean arterial pressure were measured at end-expiration. The maximal pulse pressure and the subsequent minimal pulse pressure were determined on three consecutive breaths, and ΔPP was calculated as the average of these three consecutive ΔPPs. Arterial and mixed-venous blood samples were obtained at baseline, and blood gases were measured (ABL; Radiometer, Copenhagen, Denmark), and the oximetry catheter was calibrated. At the other times, pulse oximetry and continuous measurements of mixed venous oxygen saturation (SvO_2) were used. When PiCCO was used, central venous blood gases were obtained at each time point.

Transesophageal echocardiographic evaluation was performed simultaneously with the other hemodynamic measurements (Sonos 55OO; Philips, Eindhoven, The Netherlands). At baseline, we measured left ventricular end-diastolic area and volume (Simpson rule), ejection fraction, and left ventricular outflow tract. At each time point, we measured the aortic flow time velocity integral (VTIao, to ensure the validity of cardiac output measurements at high RRs) and respiratory variations in aortic flow (ΔVao),[8,14] in pulmonary artery flow (Δpulm art), in mitral E wave, and in the systolic component of the left superior pulmonary vein flow.[4] The respiratory variations in superior vena cava (SCV) diameter were also measured,[9] and caval index was calculated as 100 × (maximal SVC diameter − minimal SVC diameter)/maximal diameter).[9] All these measurements had to be obtained within 3 min at high RRs; accordingly, we prioritized acquisition of caval index and ΔVao when signal acquisition was difficult.

To measure intrinsic PEEP, total PEEP was measured at each RR by using an expiratory hold maneuver, and the driving pressure was calculated as the difference between plateau pressure and total PEEP.

Statistical Analyses

Statistical analyses were performed using STAT View for Windows, version 5 (SAS Institute, Cary, NC) and SPSS version 13 (SPSS Inc, Chicago, IL). Nonparametric tests were used as the data were not normally distributed. The data were analyzed by a Friedman test followed by a Wilcoxon rank test with Bonferroni adjustment for multiple comparisons. The Classification and Regression Tree (CART) method was used to determine the best cutoff of HR to RR ratio for classification of ΔPP values above or below 10%.[15]

When applicable, correlations were evaluated by Spearman rho coefficient. Data are presented as median (percentiles 25–75), unless stated otherwise. Statistical significance was determined at the 95% confidence level.

Results

Seventeen patients were included. (see table, Supplemental Digital Content 1, which shows the admission characteristics of the patients, http://links.lww.com/A999). Intensive care unit survival was 75%. Baseline hemodynamic and respiratory variables are shown in table 1. Of the 17 patients, 12 were evaluated at the four time points (baseline, increase in RR to 30 and 40 breaths/min, and after fluid challenge); in five patients, the maximal RR achieved was 30 breaths/min. Measurements of ΔPP and ΔVao and caval index were obtained at all time points in all patients, measurements of VTIao in 8 patients, pulmonary artery flow in 7, pulmonary vein flow in 13, and mitral flow in 12.

Increasing RR from baseline to 30 and then 40 breaths/min did not alter total PEEP, although intrinsic PEEP increased occasionally (in five patients) (see figure, Supplemental Digital Content 2, which shows total PEEP levels in each individual patient at each step of the protocol, http://links.lww.com/A1000). Similarly, plateau pressure, and hence driving pressure, remained stable (table 2) (see table, Supplemental Digital Content 3, which shows the various hemodynamic and respiratory variables at baseline and at maximal RR achieved, http://links.lww.com/A1001). As defined per protocol, tidal volume and inspiratory to expiratory time ratio remained unchanged. All global hemodynamic variables (heart rate, central venous pressure, cardiac index, VTIao, Sa_{O_2}, Sv_{O_2}) did not change significantly during changes in RR (table 2) (Supplemental Digital Content 3, http://links.lww.com/A1001). Mitral E wave also remained unchanged (60 [51–79] cm/s at baseline and 58 [53–70] cm/s at higher RR, P = not significant).

The respiratory variation of left heart indices decreased markedly during changes in RR from 14–16 breaths/min to 30 and then 40 breaths/min (table 2; fig. 1). In particular, ΔPP became negligible when the HR to RR ratio was less than or equal to 3.6 (fig. 2). The CART method identified a cutoff value of 3.6, which yielded a risk estimate of wrong classification of 2.4%. Caval index and respiratory changes in pulmonary artery flow were unaffected by changes in RR.

After fluid challenge, cardiac index, and mean arterial pressure increased, and all dynamic indices decreased

Table 1. Baseline Hemodynamic and Respiratory Variables

Heart rate, beats/min	107 (81–116)
Mean arterial pressure, mmHg	65 (60–71)
Mean pulmonary artery pressure,* mmHg	22 (19–26)
Pulmonary artery occluded pressure,* mmHg	14 (8–17)
Central venous pressure, mmHg	11 (8–13)
Cardiac index,† $l \cdot min^{-1} \cdot m^{-2}$	2.27 (1.88–2.73)
Ejection fraction, %	49 (43–55)
pH	7.36 (7.31–7.42)
$Paco_2$, mmHg	34 (32–35)
Pa_{O_2}, mmHg	91 (87–135)
Sa_{O_2}, %	98 (96–100)
Sv_{O_2},† %	62 (53–67)
Hemoglobin concentration, g/dl	10.0 (8–10.3)
Arterial lactate concentration, mEq/l	4.0 (2.5–6.9)
Dobutamine, n (dose $\mu g \cdot kg^{-1} \cdot min^{-1}$)	8 (7 [4–180])
Dopamine, n (dose $\mu g \cdot kg^{-1} \cdot min^{-1}$)	11 (20 [13–20])
Norepinephrine, n (dose $\mu g \cdot kg^{-1} \cdot min^{-1}$)	11 (0.55 [0.18–0.97])
Tidal volume, ml/kg IBW	8.5 (8.2–9.2)
Respiratory rate, n/min	15 (14–16)
Fi_{O_2}	0.5 (0.4–0.5)
Inspiratory/expiratory time ratio	0.3 (0.3–0.3)
PEEP, cm H_2O	6 (5–9)
Plateau pressure, cm H_2O	20 (19–27)

* Data available only for 13 patients. † Sv_{O_2}: mixed-venous in 13 and central venous in 4 patients.

IBW = ideal body weight; PEEP = positive end-expiratory pressure; Sv_{O_2} = mixed venous oxygen saturation.

Table 2. Evolution of the Various Hemodynamic Variables During Changes in Respiratory Rate (RR) and During Fluid Loading

	RR 14–16 breaths/min, n = 17	RR 30 breaths/min, n = 17	RR 40 breaths/min, n = 12	RR 14–16 breaths/min + Fluids, n = 17
Global hemodynamic variables				
HR, beats/min	107 (81–116)	110 (82–118)	115 (108–120)	95 (82–106)
HR/RR	7.1 (6.6–8.0)	3.7 (2.7–3.9)†	2.9 (2.7–3.0)†‡	6.4 (6.1–7.6)
MAPee, mmHg	65 (62–72)	67 (58–75)	72 (62–78)	77 (72–85)†
CVP, mmHg	11 (8–13)	11 (9–13)	13 (11–16)	14 (10–18)†
CI, $l \cdot min^{-1} \cdot m^{-2}$	2.27 (1.88–2.73)	2.27 (1.75–2.82)	2.38 (1.98–2.96)	2.79 (2.39–3.55)†
VTIao, cm	12 (10–13)	12 (10–13)	11 (10–14)	16 (13–17)†
Sao_2, %	98 (96–100)	97 (96–100)	97 (96–100)	98 (95–100)
Svo_2, %	62 (53–67)	64 (54–69)	64 (41–70)	68 (61–75)†
Left heart respiratory variations				
ΔPP, %	21 (18–31)	11 (5–14)†	6 (2–6)†§	10 (6–13)†
ΔVAo, %	23 (18–28)	12 (7–15)†	6 (4–9)†§	9 (8–14)†
Δ Mitral E wave, %	23 (20–31)	19 (11–30)*	9 (7–13)*‡	19 (14–22)*
Δ v pulm syst, %	37 (23–48)	22 (19–33)	11 (5–22)*‡	18 (14–40)
Right heart respiratory variations				
Δ pulm art, %	31 (22–45)	37 (20–42)	35 (20–39)	27 (18–34)
Caval index (SVC), %	38 (27–43)	35 (26–40)	34 (22–44)	11 (8–17)†
Respiratory mechanics				
PEEPtot, cm H_2O	6 (5–9)	6 (5–9)	6 (5–9)	6 (5–9)
Driving pressure, cm H_2O	15 (13–19)	16 (15–19)	17 (15–22)	15 (13–18)

* $P < 0.05$ and † $P < 0.01$ *vs.* baseline; ‡ $P < 0.05$ and § $P < 0.01$ respiratory rate (RR) 40 breaths/min *vs.* RR 30 breaths/min.

CI = cardiac index; CVP = central venous pressure; HR = heart rate; MAPee = end-expiratory mean arterial pressure; Δmitral E wave = respiratory variation in mitral E wave (n = 10); PEEPtot = total positive end-expiratory pressure; Δ pulm art = respiratory variation in pulmonary artery peak velocity (n=6); ΔPP = pulse pressure variation; SVC = superior vena cava; ΔVAo = respiratory variation in peak aortic flow; VTIAo = velocity time integral of aortic flow; Δ v pulm syst = respiratory variation in the systolic component of the pulmonary vein velocity (n = 11).

(table 2), confirming the fluid responsiveness in all these patients.

As expected, an excellent correlation was observed between ΔPP and ΔVao (see figure, Supplemental Digital Content 4, which shows the relationship between ΔPP and ΔVao, http://links.lww.com/A1002). More importantly, the influence of the RR on the dissociation of right and left indices was illustrated by the fact that ΔPP was related to respiratory changes in mitral E wave and respiratory changes in the systolic component of pulmonary vein flow but not to respiratory variations in pulmonary artery flow and caval index (fig. 3) (see table, Supplemental Digital Content 5, which shows the correlation between ΔPP and other indices of fluid responsiveness, http://links.lww.com/A1003). Although ΔPP was not correlated with caval index when all RR were taken into account, a good correlation was observed between these two variables for measurements obtained at a RR of 14–16 breaths/min (baseline and after fluid challenge), but not at high (30 and 40 breaths/min) RR (fig. 3). However, respiratory variation in pulmonary artery flow was correlated with caval index (Spearman rho 0.800, $P < 0.0001$), and this relation was not affected by RR (see figure, Supplemental Digital Content 6, which shows the relationship between respiratory variations in pulmonary artery flow and caval index, http://links.lww.com/A1004).

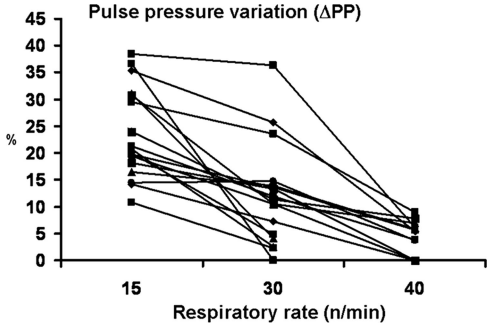

Fig. 1. Evolution of pulse pressure variation (ΔPP) at each respiratory rate. Data from individual patients are reported.

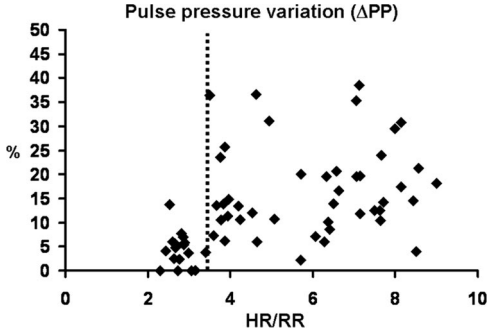

Fig. 2. Relationship between pulse pressure variation (ΔPP) and heart rate to respiratory rate ratio (HR/RR). During increases in respiratory rate, ΔPP became negligible when HR/RR ratio was less than or equal to 3.6. Below this cutoff, ΔPP can no longer be used to predict fluid responsiveness. In this figure, 12 patients contributed with 4 points, and 5 patients contributed with 3 points, depending on the maximal RR achieved.

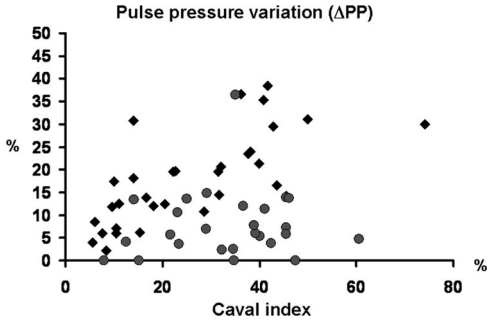

Fig. 3. Relationship between pulse pressure variation (ΔPP) and caval index. For the entire set of data, no significant correlation was found between the two variables (Spearman rho coefficient 0.247, *P* = not significant). In patients ventilated with a respiratory rate (RR) of 14–16 breaths/min (*black diamonds*), a significant relationship was observed between the two variables (Spearman rho coefficient 0.747; *P* < 0.0001), whereas no significant correlation was found between the two variables in patients ventilated at RR of 30 and 40 breaths/min (*gray circles*) (Spearman rho coefficient 0.155, *P* = not significant). This illustrates that right and left indices of preload dependency can be dissociated at high RR. In this figure, 12 patients contributed with 4 points, and 5 patients contributed with 3 points, depending on the maximal RR achieved.

Discussion

Our study indicates that respiratory variations in left ventricular stroke volume can be influenced by the RR and that right and left indices of fluid responsiveness can be dissociated in these conditions.

What mechanism can be implicated to account for these observations? The likely cause is the pulmonary transit time, which becomes too long in relation to the respiratory cycle at high RRs. In these conditions, the impact of the decreased left ventricular preload due to a decreased right ventricular ejected volume merges with the increased left ventricular preload due to the purge effect of inspiration on the pulmonary vascular bed. Accordingly, left ventricular preload does not vary significantly during mechanical ventilation at high RRs. This phenomenon was illustrated in our study by the decrease in respiratory variation in pulmonary vein flow and mitral E wave at high RRs. The absence of changes in caval index and respiratory variations in pulmonary artery flow as well as the absence of changes in cardiac output and Svo_2 during these maneuvers suggest that the changes in RR did not induce major changes in preload.

Morgan *et al.*[6] already suggested that slower RRs and HRs were associated with more marked variations in stroke volume, but no specific cutoff value was defined above which stroke volume variations became negligible. We propose that the HR to RR ratio may be used to evaluate the likelihood that stroke volume will be affected by the RR. A decrease in HR to RR ratio is accompanied by a decrease in the number of beats in both inspiratory and expiratory phases. However, the decrease in left ventricular stroke volume occurs during expiration so that the HR to RR ratio at which stroke volume variations may disappear is likely to be dependent on the inspiratory/expiratory ratio and to appear sooner, when the inspiratory to expiratory time ratio is greater than 0.3 as in this study.

Interestingly, respiratory variations in superior vena cava (caval index) and in pulmonary artery flow were not affected by the increase in RR. These observations suggest that right ventricular stroke volume still varied with ventilation at high RRs, whereas left ventricular stroke volume remained relatively constant. Thus, respiratory variations in superior vena cava diameter can be used to predict fluid responsiveness independent of RR. However, as respiratory variations in vena cava diameter only reflect respiratory variations in right ventricular preload, one should be aware that the observation of respiratory variations in the superior vena cava may not always imply fluid responsiveness, as one may consider, at least theoretically, that some patients with severe isolated left heart failure may have right but not left indices of fluid responsiveness.

Other factors may have affected the cardiovascular state at different RRs. First, intrinsic PEEP may have developed at a high RR. The impact of intrinsic PEEP may be dual, potentially decreasing driving pressure on one hand (but this effect may be variable, depending on the effects of intrinsic PEEP on lung compliance), but also decreasing right ventricular preload and thus increasing stroke volume variation on the other hand.[2] Intrinsic PEEP, measured by the occlusion pressure, remained unchanged in the majority of the patients, even though it occurred in one-third of patients (3 at 30 breaths/min and 2 additional patients at 40 breaths/min). This had a minor impact on right and left ventricular preload as the mitral E wave, an index of left ventricular preload, and cardiac output remained unchanged in most of the patients. In addition, the lack of changes in right-sided indices of fluid responsiveness indicates that the impact of these phenomena was quite limited. Driving pressure increased slightly, probably due to an alteration in lung compliance induced by the small increase in intrinsic PEEP. Accordingly, the effects of intrinsic PEEP cannot explain our findings. Second, changes in pH and $Paco_2$ may have affected vascular tone, and hence the cardiovascular response. We did not measure $Paco_2$ at high RRs; if present, the impact of these changes was of small magnitude, as most hemodynamic variables were unaltered.[16,17] In addition, the time spent at a high RR was very limited, and a longer period of time is usually required to achieve significant changes in $Paco_2$ because it requires equilibration with dissolved tissue carbon dioxide stores (which are close to 15 l in normal humans at $Paco_2$ of 40 mmHg).[18] In addition, changes in $Paco_2$ induced by changes in RR may be limited, especially in patients with acute respiratory distress syndrome.[19] Finally, errors in measurements may have affected our results. However, the excellent correlation of respiratory changes in pulse pressure and aortic

flow, two closely related measurements, suggests that errors in measurements played a minimal role. We also measured VTIao to ensure that measurements of cardiac output by thermodilution were not affected by changes in ventilatory settings. The evolution of VTIao and cardiac output were similar, confirming the absence of change in cardiac index during changes in ventilatory rate and a positive response to fluid administration.

One may argue that in many cases RR is unlikely to play a significant role, as an HR to RR ratio less than or equal to 3.6 is relatively uncommon. However, RRs close to or even above 30 breaths/min are often used in patients with acute respiratory distress syndrome ventilated with small tidal volumes,[11,20] and an HR to RR ratio less than or equal to 3.6 may occur in these patients; indeed, an HR to RR ratio less than or equal to 3.6 was observed in one-third of our population at a RR of 30/min. An HR to RR ratio less than or equal to 3.6 may also occur in patients treated with β-blockers or other antiarrhythmic agents ventilated at more conventional RRs. It is likely that disappearance of stroke volume variation may even occur at higher HR to RR ratios if inspiratory to expiratory time ratios are greater than 0.3.

Finally, this study further highlights that respiratory changes in left ventricular preload can be evaluated by echocardiography, with the analysis of respiratory changes in mitral or pulmonary vein flows.[4] This approach may be useful in patients ventilated with low tidal volumes, to differentiate an absence of fluid responsiveness from an insufficient change in preload.

In conclusion, stroke volume variations may be abolished at high RRs. This may limit the predictive value of these indices for fluid responsiveness in patients ventilated at high RRs in the context of protective lung ventilation or severe metabolic acidosis and may contribute to their poor usefulness in tachypneic patients breathing spontaneously. At high RRs, respiratory changes in right and left ventricular preload can be dissociated.

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