Impact of Respiratory Rate and Dead Space in the Current Era of Lung Protective Mechanical Ventilation

François Lellouche, MD, PhD
Mathieu Delorme, PT
Québec, QC, Canada
Laurent Brochard, MD, HDR
Toronto, ON, Canada

Protective ventilation should potentially be applied in most or all patients undergoing invasive mechanical ventilation.[1,2] Reduction of tidal volume (V_T) has progressively been incorporated over the years.[3] Protective ventilation is not limited to V_T reduction, however, but needs a combination of ventilator settings and associated procedures.[1,4] The progressive reduction of V_T has necessitated to increase the respiratory rate (RR), but no clear recommendation for setting the rate exists. In addition, the impact of dead space, including instrumental dead space (V_{Dinstr}), became highly relevant. Reducing the V_{Dinstr} should be recommended as part of lung protective ventilation,[4] especially for patients requiring $V_T \leq 6$ mL/kg of predicted body weight (PBW).[5] In this report, we reviewed data from the literature of the last 20 years to try to offer some clues to physicians on the questions of rate setting and the impact of dead space.

AFFILIATIONS: From the Centre de Recherche de l'Institut Universitaire de Cardiologie et de Pneumologie de Québec (Dr Lellouche and Mr Delorme), Université Laval; the Université Paris-Saclay (Mr Delorme), UVSQ, ERPHAN, Versailles, France; the Keenan Research Centre for Biomedical Science (Dr Brochard), Li Ka Shing Knowledge Institute, St Michael's Hospital; and the Interdepartmental Division of Critical Care (Dr Brochard), University of Toronto.

FINANCIAL/NONFINANCIAL DISCLOSURES: The authors have reported to *CHEST* the following: F. L. developed a free application (VentilO) to set the ventilator with protective ventilation and to optimize the settings. The application was funded by Fisher & Paykel. L. B. received research grants from Medtronic Covidien and Fisher & Paykel, and equipment from Fisher & Paykel, Philips, and Sentec. None declared (M. D.).

CORRESPONDENCE TO: François Lellouche, MD, PhD, Centre de recherche de l'Institut universitaire de cardiologie et de pneumologie de Québec, 2725, Chemin Sainte-Foy, G1V4G5, Québec, QC, Canada; e-mail: francois.lellouche@criucpq.ulaval.ca

DOI: https://doi.org/10.1016/j.chest.2020.02.033

Initial Minute Ventilation and Settings in the Era of Lung Protective Mechanical Ventilation

More than 50 years ago, a minute ventilation of ≤ 100 mL/kg $_{PBW}$/min was recommended for surgical populations, which was increased by 10% for each degree Celsius above 37°C and decreased by 10% for each degree Celsius below 37°C.[6,7] Even if a strictly normal Pa_{CO_2} level is not targeted, this estimate cannot be used for critically ill patients undergoing mechanical ventilation. Ventilator settings used in the operating room and in critically ill target patients with different dead space and CO_2 production (because of metabolism, temperature, presence of sepsis, vasopressors, etc). In addition, more V_{Dinstr} is frequently added to the circuit of patients in the ICU, as subsequently discussed.

Figure 1 uses the literature and differentiates scheduled surgical patients (planned surgery) and patients in the ICU. In patients undergoing mechanical ventilation for planned surgery, the V_T is often between 8 and 10 mL/kg $_{PBW}$ and the RR is often < 15 breaths/min. In critically ill patients in whom protective ventilation is increasingly used, V_T is close to 6 mL/kg $_{PBW}$ and the RR is often > 25 or 30 breaths/min. Data presented in Figure 1 show that the 100 mL/kg $_{PBW}$/min minute ventilation recommended > 60 years ago by Radford et al[6] is still used in surgical patients. In contrast, for patients in the ICU, a minute ventilation of at least 150 mL/kg $_{PBW}$/min is more often used. These data indicate that the RR needed to achieve this target in patients in the ICU is at least 25 breaths/min when a V_T of ≤ 6 mL/kg $_{PBW}$ is used, even if a mild degree of hypercapnia is often accepted.

Impact of Dead Space During Protective and Ultraprotective Mechanical Ventilation

Reducing V_{Dinstr} by replacing a heat and moisture exchanger (heat and moisture exchanger [HME]) by a heated humidifier improves CO_2 elimination[8] or allows reduction in V_T and plateau pressure for a constant Pa_{CO_2}.[8] Such data were published about 15 years ago, when V_T values were around 8 mL/kg and RRs were around 20 breaths/min. With the widespread use of

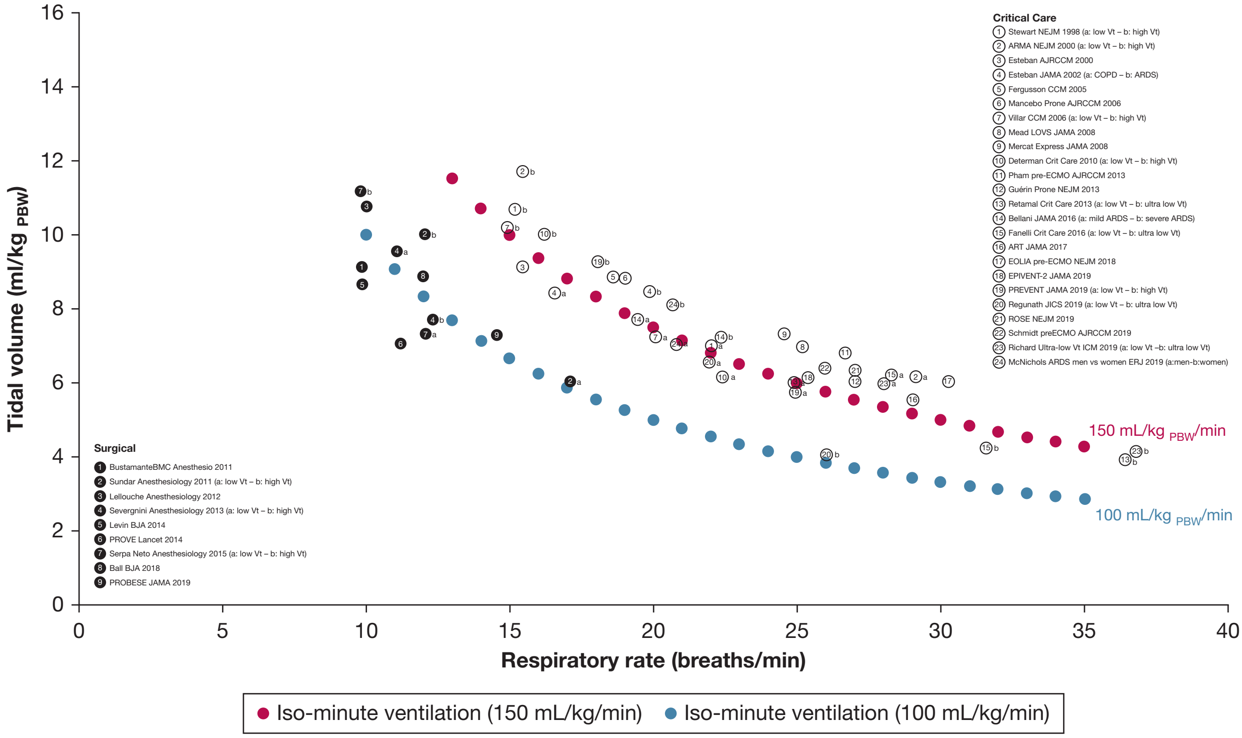

Figure 1 – *Ventilation data (V_T in mL/kg $_{PBW}$ and respiratory rate [RR]) used in surgical studies conducted in the operating room (black circles) and ICU (white circles) in chronologic order are shown. The iso-minute ventilation lines for 100 and 150 mL/kg $_{PBW}$/min are represented, respectively, in blue and red. Minute ventilation is usually around 100 mL/kg $_{PBW}$ in patients under mechanical ventilation during surgery and at least 150 mL/kg $_{PBW}$/min in patients in the ICU. Minute ventilation is even higher ($\geq$ 180 mL/kg $_{PBW}$/min) in several studies. In the operating room, the RR used is most of the time $<$ 15 breaths/min, and in patients in the ICU with protective mechanical ventilation, the RR used is $>$ 20 breaths/min in most studies and frequently $>$ 25 breaths/min. Some studies, for which all ventilatory data were not available, could not be represented on this graph. PBW = predicted body weight; V_T = tidal volume.*

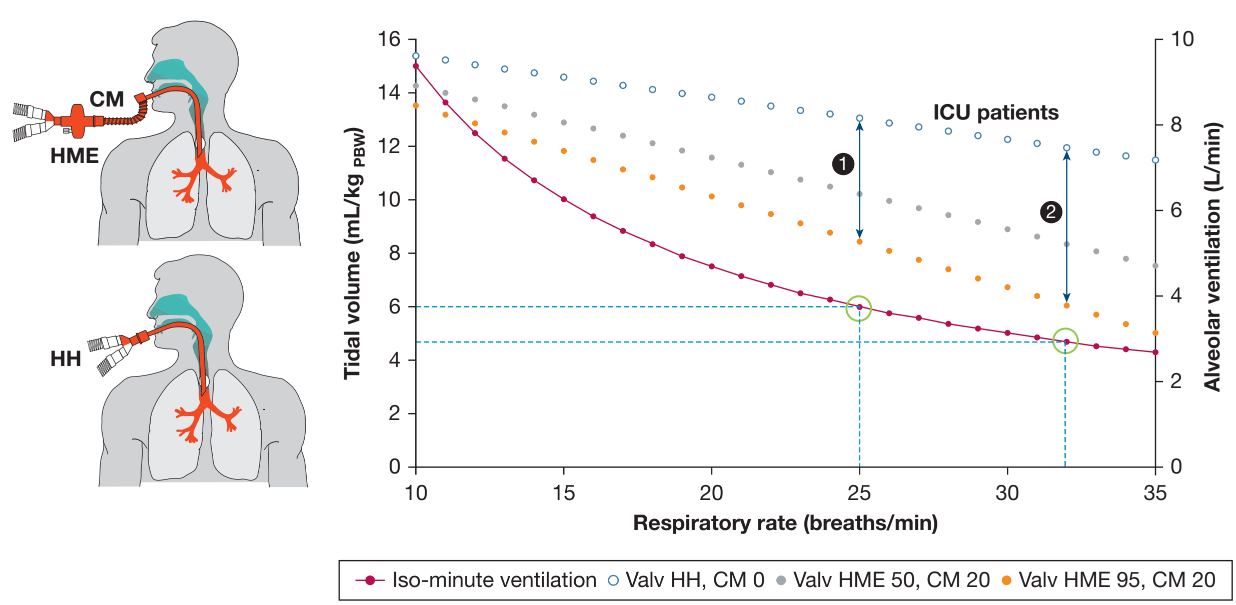

Figure 2 – *The impact of dead space on alveolar ventilation (Valv) for different settings that provide the same minute ventilation (iso-minute ventilation red line, corresponding to 150 mL/kg $_{PBW}$/min in a 175-cm man) is shown. In patients in the ICU with protective ventilation, the impact of dead space (V_D) can be substantial. For a V_T of 6 mL/kg $_{PBW}$ with a RR of 25 breaths/min (case 1), the alveolar ventilation increases from 5.3 to 8.1 L/min by reducing the V_D to a minimum. For a V_T of 4.7 mL/kg $_{PBW}$ with a RR of 32 breaths/min (case 2), alveolar ventilation increases by twofold from 3.8 to 7.5 L/min, reducing V_D to a minimum. In these situations, it is crucial to minimize the instrumental dead space as much as possible to prevent the accumulation of CO_2.[5] The dead space volume is represented in red in the setting with HME and CM (other possible connectors are not represented) and in the setting with heated humidification, without CM. By definition, during invasive mechanical ventilation, the dead space is the volume with high CO_2 concentration during expiration that will be reinhaled during the next respiration cycle. See Figure 1 legend for expansion of other abbreviations. CM =catheter mount; HH = heated humidifier; HME = heat and moisture exchanger; Valv = alveolar ventilation.*

protective or ultraprotective ventilation in adults with RRs often > 25 breaths/min,[3] any fixed portion of dead space becomes even more relevant, as has been the case for pediatrics for many years.[9]

Alveolar ventilation (V_{alv}) is the part of ventilation that is effective for CO_2 elimination, whereas dead space ventilation is the ineffective part. Total dead space can be seen as the addition of the physiological dead space (V_{Dphys}) and the instrumental dead space (V_{Dinstr}). V_{Dinstr} is the volume after the Y-piece (and including part of the Y-piece) up to the end of the endotracheal tube or tracheostomy tube. V_{Dinstr} includes the volume of HME when present (range, 30-95 mL), any connectors (catheter mounts, connector for end-tidal CO_2 monitoring, connector for closed suction circuits, etc), and endotracheal (11-24 mL, depending on their length and diameter) and tracheostomy tubes (3-8 mL, depending on their length and diameter). V_{Dphys} can be estimated at 2.2 mL/kg $_{PBW}$ (1 mL/lb of PBW). Radford et al[6] stated “a remarkable, but approximate rule that the respiratory dead space in milliliters equals the body weight in pounds.” In patients on mechanical ventilation, because of the exclusion of the bypassed upper airways, V_{Dphys} is approximately one-half of the V_{Dphys} in patients who are not intubated.[10] This may vary, however, according to the anatomy of each subject, sex, position, age, and pathology. During ARDS and in the case of overdistension leading to increased alveolar dead space, V_{Dphys} may be much higher than estimated. As shown in Figure 2, using a simple formula and comparing the effect of V_{Dinstr} reduction on Pa_{CO_2}, it is easy to assess the impact of this part of the dead space: $V_{alv} = (V_T - V_{Dtotal}) \times RR$; $V_{alv} = [V_T - (V_{Dinstr} + V_{Dphys})] \times RR$, where V_{Dtotal} is the total dead space. With a constant dead space, if V_T decreases, dead space/V_T increases. In addition, instead of being present 10 or 15 times per minute, the gas in the instrumental and anatomic dead space is reinhaled 25 to 30 times per minute, leading to a further decrease in V_{alv}. Figure 2 therefore illustrates that during protective ventilation, with reduced V_T and elevated RRs, dead space/V_T is increased and V_{alv} can be substantially increased by reducing V_{Dinstr} (removal of catheter mounts or other connectors and HMEs) (ie, enhancing the efficiency of minute ventilation). The other option to increase V_{alv} would be to increase V_T or RR. However, during protective ventilation, the aim is usually to further decrease the V_T and the RR is already high and limited by potential intrinsic positive end expiratory pressure.

Conclusions

The use of lung protective ventilation with V_T around 6 mL/kg $_{PBW}$ in critically ill patients often necessitates RRs to be ≥ 25 breaths/min. V_{Dinstr} must be minimized when protective ventilation is used, especially when the RR is > 25 breaths/min, or when V_T is ≤ 6 mL/kg $_{PBW}$.[4] Improved V_{alv} can improve CO_2 elimination when acidosis is critical,[4,8] and consequently reduce the respiratory drive.[11] If the physician chooses to keep Pa_{CO_2} constant, reduction of V_{Dinstr} allows a reduction of V_T, plateau pressure, driving pressure, and power, or a reduction of the RR and power.

References

1. Fan E, Brodie D, Slutsky AS. Acute respiratory distress syndrome: advances in diagnosis and treatment. *JAMA*. 2018;319(7):698-710.
2. Serpa Neto A, Cardoso SO, Manetta JA, et al. Association between use of lung-protective ventilation with lower tidal volumes and clinical outcomes among patients without acute respiratory distress syndrome: a meta-analysis. *JAMA*. 2012;308(16):1651-1659.
3. Schaefer MS, Serpa Neto A, Pelosi P, et al. Temporal changes in ventilator settings in patients with uninjured lungs: a systematic review. *Anesth Analg*. 2019;129(1):129-140.
4. Papazian L, Aubron C, Brochard L, et al. Formal guidelines: management of acute respiratory distress syndrome. *Ann Intensive Care*. 2019;9(1):69.
5. Richard JC, Marque S, Gros A, et al. Feasibility and safety of ultra-low tidal volume ventilation without extracorporeal circulation in moderately severe and severe ARDS patients. *Intensive Care Med*. 2019;45(11):1590-1598.
6. Radford EP Jr, Ferris BG Jr, Kriete BC. Clinical use of a nomogram to estimate proper ventilation during artificial respiration. *N Engl J Med*. 1954;251(22):877-884.
7. Kenny S. The Adelaide ventilation guide. *Br J Anaesth*. 1967;39(1):21-23.
8. Moran I, Bellapart J, Vari A, Mancebo J. Heat and moisture exchangers and heated humidifiers in acute lung injury/acute respiratory distress syndrome patients. Effects on respiratory mechanics and gas exchange. *Intensive Care Med*. 2006;32(4):524-531.
9. Pearsall MF, Feldman JM. When does apparatus dead space matter for the pediatric patient? *Anesth Analg*. 2014;118(4):776-780.
10. Nunn JF, Campbell EJ, Peckett BW. Anatomical subdivisions of the volume of respiratory dead space and effect of position of the jaw. *J Appl Physiol*. 1959;14(2):174-176.
11. Vaporidi K, Akoumianaki E, Telias I, Goligher EC, Brochard L, Georgopoulos D. Respiratory drive in critically ill patients: pathophysiology and clinical implications. *Am J Respir Crit Care Med*. 2020;201(1):20-32.