Resuscitation 82 (2011) 1444–1452

Contents lists available at ScienceDirect

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Simulation and education

A structural model of perfusion and oxygenation in low-flow states☆

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ARTICLE INFO

Article history:
Received 5 January 2011
Received in revised form 11 May 2011
Accepted 18 May 2011

Keywords:
Ventilation
Perfusion
Shock
Oxygenation
Tidal volume
Cardiac output

ABSTRACT

Background: Recent investigations underscore the critical importance of ventilation strategies on resuscitation outcomes. In low perfusion states, such as cardiac arrest and traumatic shock, the rise in intrathoracic pressure that accompanies positive-pressure ventilation can significantly impede venous return and lead to a decrease in cardiac output. The optimal ventilation strategy in these "low-flow" states remains unclear.
Objective: To create a mathematical model of perfusion and oxygenation to predict the effects of PPV with both normotension and hypotension.
Methods: The lung pressure–volume relationship was modeled using a novel formula allowing manipulation of various lung characteristics. A separate formula was then derived to predict mean intrathoracic pressure (MITP) for specific minute ventilation values using the pressure–volume formula. The addition of positive end-expiratory pressure was also modeled. Finally, a formula was derived to model oxygen absorbance as a function of alveolar surface area and flow based on ventilation rate and MITP.
Results: Mathematical models of the lung pressure–volume relationship, MITP, and absorbance were successfully derived. Manipulation of total lung capacity, compliance, upper and lower inflection points, positive end-expiratory pressure, and minute ventilation allowed prediction of optimal ventilation rate and tidal volume for a normal lung and with various abnormal characteristics to simulate particular disease states, such as acute respiratory distress syndrome (ARDS). For a normal lung, ventilation rates of 4–6 breaths/min with higher tidal volumes (15–20 mL/kg) resulted in the lowest predicted MITP values (5 cm H_2O) and the highest absorbance. The input of lung parameters that would simulate ARDS resulted in optimal ventilation rates of 10–12 breaths/min with lower tidal volumes (8–10 mL/kg) and higher predicted MITP values (10–15 cm H_2O).
Conclusions: A mathematical model of ventilation was successfully derived allowing manipulation of multiple pulmonary physiological variables to predict MITP and potentially identify optimal ventilation strategies. This model suggests the use of lower ventilation rates and larger tidal volumes to minimize the hemodynamic effects of positive pressure ventilation in patients with hypoperfusion but normal lung characteristics.

1. Introduction

Multiple recent investigations underscore the critical importance of avoiding hyperventilation during resuscitation from traumatic brain injury (TBI), hypovolemic shock, and cardiac arrest.[1–6] Cerebral perfusion is highly sensitive to even small changes in [CO2], with hypocapnia leading to the rapid onset of cerebral vasoconstriction and ischemia.[7–9] In addition, the mean intrathoracic pressure (MITP) rise that accompanies positive-pressure ventilation can impede venous return and decrease cardiac output, especially in low-perfusion states.[4–6] Guides to ventilation have generally included the use of either quantitative capnometry in TBI patients or application of prescribed ventilation rates or compression-to-ventilation ratios in cardiac arrest.[10,11]

Optimal ventilation strategies have been defined for intensive care unit (ICU) patients with acute respiratory distress syndrome (ARDS) to maximize surface area for oxygen absorption and to minimize pulmonary injury due to barotrauma, biotrauma, and atelectrauma.[12–19] This has led to the widespread application of "lung-protective ventilation" in this patient population, generally resulting in smaller tidal volumes and faster ventilation rates with the use of positive end-expiratory pressure (PEEP). These patients are usually not suffering ongoing hemorrhage, are generally

☆ A Spanish translated version of the abstract of this article appears as Appendix in the final online version at doi:10.1016/j.resuscitation.2011.05.028.

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doi:10.1016/j.resuscitation.2011.05.028

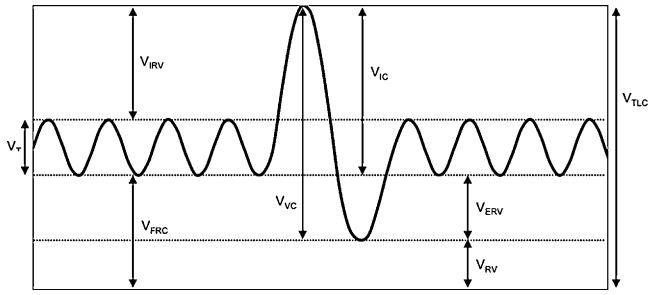

Fig. 1. Pulmonary volumes during normal breathing and with maximal inspiration, and theoretical model of lung function.

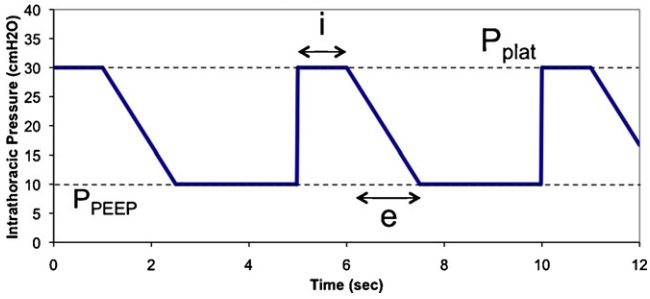

Fig. 3. Pressure–volume cycle over time.

euvolemic, and may be on pressor therapy to offset the negative hemodynamic effects of positive-pressure ventilation. These may not be true with acute resuscitation, where absolute or relative hypovolemia may be present.

Optimal tidal volumes and ventilation rates in hypoperfusion states remain poorly defined, potentially involving the dynamic interaction between minute ventilation and pCO_2, the rise in MITP that accompanies positive-pressure ventilation, and changes in alveolar surface area. Here we derive a structural model to predict MITP and oxygen absorption trends with changes in ventilation rate and tidal volume at varying degrees of hypotension. We hypothesized that lower ventilation rates and larger tidal volumes than used in conventional practice would be optimal with regard to both hemodynamics and oxygen absorption in low perfusion states.

2. Methods

2.1. Pulmonary pressure–volume curve

The first objective in deriving a structural model of perfusion and oxygenation was to define the variational relationship between total lung volume (V) and intrapulmonary pressure (P). This relationship was modeled using the nomenclature of Figs. 1–3. Fig. 1 demonstrates normal breathing with a single breath of maximum inhalation followed by maximum exhalation. Fig. 2 defines a sinusoidal curve containing a lower inflection point (LIP) and an upper inflection point (UIP). The LIP represents the transition from the relatively pressure-inefficient phase with initial inflation

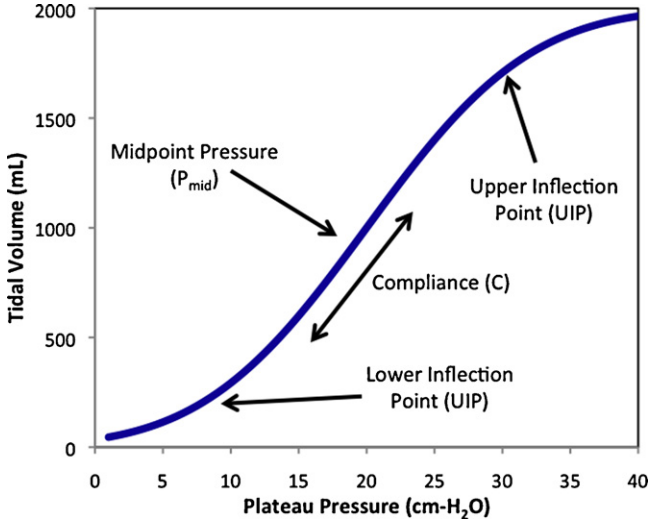

Fig. 2. Intrathoracic pressure versus tidal volume model. This curve uses standard lung parameters (solid; $K = 0.5$, $V_{VC} = 4$ L, $P_{mid} = 20$, $C = 9.5$, PEEP = 0, $i = 1$, $e = 2$, $V_D = 350$, Wt = 80 kg, VE = 6.4 L).

of atelectatic alveoli to more efficient lung volumes. The UIP represents the transition into an "overstretch" zone where relatively small increases in intrapulmonary volume (V) result in a rapid rise in intrathoracic pressures (P). Fig. 3 represents the respiratory/ventilatory cycle over time.

A three-compartment model (dead space, perfused alveoli, and non-perfused alveoli) was used, with relevant terminology defined in Table 1. The relative ratio of perfused to non-perfused lung segments is represented by the term Q, which can be approximated by the ratio of end-tidal to arterial CO_2 ($PetCO_2/PaCO_2$). The [CO_2], relative volumes, and total CO_2 contribution are displayed in Table 2. Ultimately, these calculations are important in determining the alveolar minute ventilation (VE_{alv}) requirement. Using the equation from Table 1, we can define the relationship between positive-pressure–volume (V_{PPV}) and intrapulmonary pressure (P) by the formula:

$$V_{PPV} = K \cdot V_{VC} \cdot \text{NORMDIST}(P, P_{mid}, C, 1) \quad (1)$$

This formula allows independent manipulation of various lung characteristics. Midpoint pulmonary pressure (P_{mid}) represents the pressure at the midpoint between the LIP and UIP. Compliance (C) is defined as the standard deviation of P around P_{mid}, with lower C values (i.e., steeper slope) representing a more compliant lung. The volumes at which LIP and UIP occur are defined by the input values for K, vital capacity (V_{VC}), and C. The term K allows lowering of the

Table 1
Definitions for derived equations.

General lung equation
$V = V_R + V_{PPV}$
Residual volume equations
$V_R = V_{RD} + V_{Ralv}$
$V_{Ralv} = V_{RP} + V_{RNP}$
Positive-pressure ventilation equations
$V_{PPV} = V_{PEEP} + V_T$
$V_T = V_{TD} + V_{Talv}$
$V_{Talv} = V_{TP} + V_{TNP}$
Dead space equation
$V_D = V_{RD} = V_{TD}$
Perfusion equations
$Q = V_{RP}/V_{Ralv} = V_{RP}/(V_{RP} + V_{RNP})$
$Q = V_{TP}/V_{Talv} = V_{TP}/(V_{TP} + V_{TNP})$
$Q = V_{DP}/(V_{DP} + V_{DNP})$
$Q \approx PetCO_2/PaCO_2$

V = total lung volume; V_R = residual lung volume; V_{PPV} = lung volume related to positive-pressure ventilation; V_{RD} = residual lung volume in anatomic dead space (nonconducting airways and ventilator circuit); V_{Ralv} = residual lung volume in alveoli; V_{RP} = residual lung volume in perfused alveoli; V_{RNP} = residual lung volume in nonperfused alveoli; V_{PEEP} = lung volume related to positive end-expiratory pressure; V_T = lung volume related to tidal volume ventilation; V_{TD} = tidal volume ventilation that fills anatomic dead space; V_{Talv} = tidal volume ventilation that fills alveoli; V_{TP} = tidal volume ventilation that fills perfused alveoli; V_{TNP} = tidal volume ventilation that fills nonperfused alveoli; V_D = volume of anatomic dead space; V_{DP} = volume of anatomic dead space that fills perfused alveoli; V_{DNP} = volume of anatomic dead space that fills nonperfused alveoli; $PaCO_2$ = arterial partial pressure of carbon dioxide; $PetCO_2$ = end-tidal partial pressure of carbon dioxide.