Relationship of Tidal Volume to Peak Flow, Breath Rate, I:E and Plateau Time: Mock Study

HongLei Wu, JC, WeiZhang Xiao, MM, XuJuan Xu, NM, YanHong Gu, ND, FengYing Lu, NM and JiaHai Shi, MD, PhD

Abstract: *Background:* The purpose of this study was to determine the functional relationship between tidal volume (V_T) and 4 other ventilator parameters. *Methods:* The following parameters were collected from an AVEA ventilator operating in the volume-controlled ventilation mode: V_T (in L), peak flow (V_{max}, in L/min), breath rate (f, in bpm), inspiratory-to-expiratory time ratio (I:E) and plateau time (T_P, in s). The relationship between V_T and each of the other variables was determined. *Results:* When the other parameters were held constant, V_T was positively correlated with V_{max} and I:E, but negatively correlated with f and T_P. When the velocity versus time curve was a 50% linearly decreasing wave, the functional relationship among the 5 parameters was governed by the equation: $V_T = 180\ V_{max}\ (60f - 60f\ [1 + I{:}E] - T_P)$. *Conclusions:* The functional relationship among the 5 parameters for the AVEA ventilator in the volume-controlled ventilation mode was determined. The parameters should be controlled in accordance with the patient's pathophysiological needs.

Key Indexing Terms: Ventilator; Breath rate; Tidal volume; Plateau time; Peak flow; Inspiratory-to-expiratory time ratio. **[Am J Med Sci 2015;349(4):312–315.]**

Mechanical ventilation is often used as a lifesaving intervention to restore or maintain adequate oxygenation in critically ill patients.[1] However, using improper ventilator during clinical treatment can cause ventilator-associated lung injury (VALI), pathological and functional exacerbation of lung injury and even lead to death.[2] In the actual operation process, certain functional relationships exist among the ventilator parameters. In mechanical ventilation, the setup of the ventilator modes and parameters directly affects the patient's hemodynamic, oxygenation and spontaneous breathing levels. Until now, there has not been a precise and scientific understanding of the ventilator, or of the relationships between tidal volume (V_T) and other ventilator parameters. Caretakers can only operate the equipment or guarantee its safe clinical application by experience.

The aim of this study was to determine the functional relationship between ventilator parameters for the ventilator used at our cardiac surgery intensive care unit (CSICU). Using waveform figures plotted from the ventilator data, the authors sought to derive a precise formula for this relationship. Data obtained from this report will hopefully provide a detailed guidance for the clinical use of the ventilator.

From the Cardiac Surgery Intensive Care Unit (HW, WX, XX, YG, FL, JS), Affiliated Hospital of Nantong University, Nantong City, China.

Submitted July 28, 2014; accepted in revised form November 20, 2014.
The authors have no financial or other conflicts of interest to disclose.
H.W. and W.X. contributed equally to this work.

Correspondence: JiaHai Shi, MD, PhD, Cardiac Surgery Intensive Care Unit, Affiliated Hospital of Nantong University, No. 20 Xisi Road, Nantong 226001, China (E-mail: happysjh167@163.com).

MATERIALS AND METHODS

AVEA ventilator systems (VIASYS Respiratory Care Inc. 22745 Savi Ranch Parkway Yorba Linda, CA) were used in this study. These ventilator systems could be set in the volume-controlled ventilation mode. Constant volume ventilation has several advantages. In particular, this mode can guarantee a preset tidal volume (V_T). Specifically, the doctor presets instructions for breathing patterns in the case of emergency, regardless of resistance and compliance, and the predetermined V_T is delivered.[3] In this report, experiments were performed with the test lung and lung simulators.

Type of Study

This was an interventional, prospective, controlled and nonclinical study.

Intervention

Two groups of basic ventilator parameters were set in the volume-controlled ventilation mode.

For group 1: The basic settings were $V_T = 0.76$ L, respiratory rate (f) = 12 bpm, peak velocity (V_{max}) = 40 L/min, plateau time (T_P) = 0.25 seconds and inspiratory time (T_i)-to-expiratory time (T_e) ratio (I:E) = 1:1.9.

For group 2: The basic settings were $V_T = 0.52$ L, f = 14 bpm, V_{max} = 29 L/min, T_P = 0.15 seconds and I:E = 1:1.7.

To determine the dependence of V_T on each variable, for each group, 1 variable was changed while holding 3 variables constant and recording V_T. The respiratory rate (f) started at 6 bpm and was increased by 1 bpm each time, for 15 times per group. The V_{max} started at 15 L/min and was increased by 5 L/min each time, for 15 times per group. The T_P started at 0.1 seconds and was increased by 0.1 seconds each time, for 13 times per group. The I:E ratio started at 1:6.7 and was progressively increased each time, for 18 times per group. In total, 20 sets of parameters were recorded in the SIMV/AC mode. Graphs were constructed with V_T on the y-axis and each independent variable on the x-axis in both groups.

Data Collection

All assessments of baseline characteristics and main outcome measures were performed independently by investigators who were blinded to the group allocation.

Statistical Analysis

Means and standard deviations (x ± s) are reported for normally distributed measurement data. Differences between groups were compared by the 2-sample *t* test. Repeated-measures analysis of variance (ANOVA) was used to compare between- and within-group differences. A statistical software package (IBM Corporation 2013. China International Business Machines Co. 27 beisihuanzhonglu Beijing chaoyang district. SPSS Statistics 20.0 for Windows) was used.

RESULTS

Graphs for the relationship of V_T with changes in the independent ventilator parameters f, V_{max}, T_p and I:E for the 2 groups are shown in Figures 1–4. Maximum and minimum differences in V_T between the 2 curves were 0.36 and 0.06 L, respectively, for f (Figure 1); 0.07 and 0.02 L, respectively, for V_{max} (Figure 2); 0.32 and 0.13 L, respectively, for T_p (Figure 3); and 0.695 and 0.054 L, respectively, for I:E (Figure 4). For the AVEA ventilator operated in the volume-controlled ventilation mode, V_T decreased with increasing f, with a negative correlation between the parameters. V_T increased with increasing V_{max}, with a positive correlation between the parameters. V_T decreased with increasing T_P, with a positive correlation between the parameters. Finally, V_T increased with increasing I:E, with a positive correlation between the parameters.

Figure 5 shows the velocity versus time scalar waveform (F–T curve) for the AVEA ventilator operated in the volume-controlled ventilation mode.

$$V_T = \frac{1}{80} V_{max} \left[\frac{60}{f} - \frac{60}{f\,(1 + I{:}E)} - T_P\right]$$

DISCUSSION

The Operator's Manual for the AVEA ventilator system[4] states that for a volume breath, only the calculated I:E ratio changes if the set V_T, f, or V_{max} changes. The authors found that in practice and in the derived formula T_E was negatively correlated with f, V_T and T_P, but positively correlated with V_{max}. The setup and regulation of I:E were related to V_T, f, V_{max} and T_P only. Because the AVEA Operator's Manual is not exact or sufficiently comprehensive, it will be necessary to make further additions to the functional formula between the ventilator parameters. More specifically, V_T, f, V_{max} and T_P can be manually adjusted in the AVEA ventilator system. Although I:E cannot be manually adjusted, it is influenced by V_T, f, V_{max} and T_P.

In Figure 5, the intersection points were set as the coordinates, and AB = V_{max}, AE = T_i, EG = T_e, DE = T_P and CD = 50% V_{max}.[5] The waveform was linearly decreased in the inspiratory phase and linearly increased in the expiratory phase. At the end of inspiration, the ventilator stopped delivering gas and then slowly exhaled, forming an increasing wave.

Some new findings in this study were that the area of the graph enclosed by ABCD (S_{ABCD}) = V_T and AG = 60/f. Therefore, AD + EG + T_P = 60/f or AD = $\frac{60}{f} - \frac{60}{f\,(1+I{:}E)} - T_P$. As V_{max} is measured in units of L/min and AD is measured in units of s, the authors conclude that: $V_T = \frac{1}{80} V_{max} [\frac{60}{f} - \frac{60}{f\,(1+I{:}E)} - T_P]$. This formula includes all of the parameters in the volume-controlled ventilation mode of the AVEA ventilator. According to this formula, when the other parameters are held constant, V_T shows positive relationships with V_{max}, I:E, f and T_P.

When the other parameters were held constant, T_E was negatively correlated with f, V_T and T_P, but positively correlated with V_{max}. The authors compared the V_T values calculated by the formula with the actual values to verify the correctness of formula while varying V_{max}, f, I:E and T_P. As shown in Figure 6, the actual and calculated curves for V_T were nearly overlapping, so that the above formula held true. In our analysis, the I:E value from the ventilator displayed 1 decimal only, whereas the actual I:E had 2 or more decimals. This difference led to a slight discrepancy between the 2 curves.

Figure 5 shows the velocity versus time scalar waveform (F–T curve) for the AVEA ventilator operated in the volume-controlled ventilation mode. From this figure, the authors conclude that $V_T = \frac{1}{80} V_{max} [\frac{60}{f} - \frac{60}{f\,(1+I{:}E)} - T_P]$. In the volume-controlled ventilation mode, if the F–T curve has been determined, then V_T, f, V_{max}, T_P and I:E influence and mutually restrain each other.

During mechanical ventilation, the lung is affected by various mechanical forces, including tension/strain, stress and shear force/stress effects.[6] When used improperly, mechanical ventilation can cause excessive distension of the lung tissue, changing its structure and function, as well as destroying the function of the cell barrier. The lung cells can sense mechanical force and conduct mechanical signals, leading them to produce proinflammatory cytokines and chemotactic factors. The consequent accumulation of inflammatory cells in the lung can result in various biological damages.[7] A study by Li confirmed that mechanical ventilation with a high-volume, high inspiratory flow and high-frequency leads to VALI.[8]

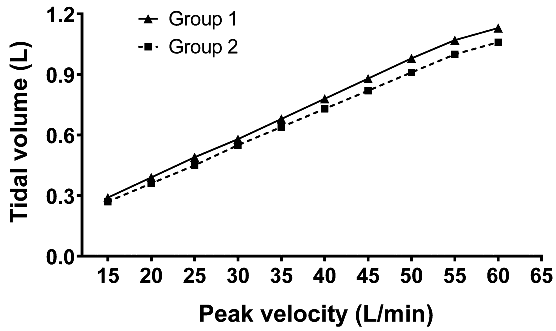

FIGURE 2. Relationship between tidal volume (V_T) and peak velocity (V_{max}).

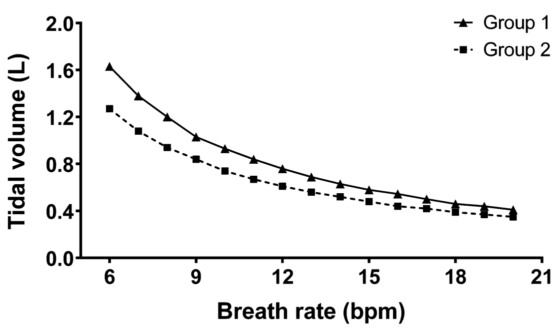

FIGURE 1. Relationship between tidal volume (V_T) and breath rate (f).

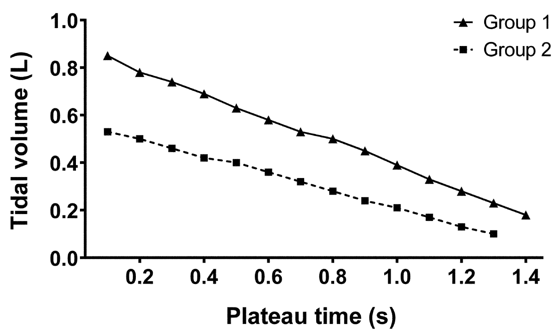

FIGURE 3. Relationship between tidal volume (V_T) and plateau time (T_P).