POSITIVE END-EXPIRATORY PRESSURE: IMPLICATIONS FOR TIDAL VOLUME CHANGES IN ANESTHESIA MACHINE VENTILATION

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Elliott WR, Harris AE, Philip JH. Positive end-expiratory pressure: implications for tidal volume changes in anesthesia machine ventilation.

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ABSTRACT. In clinical practice, the addition of positive end-expiratory pressure (PEEP) into a standard anesthesia circle circuit decreases the delivered tidal volume (DTV) to a patient. We studied the magnitude of the ΔDTV/ΔPEEP relationship in two commonly used anesthesia systems. In addition, the magnitude of the ΔDTV/ΔPEEP relationship varies with both pulmonary compliance and volume of gas contained in the patient's breathing system between the ventilator and PEEP valve site, and this was also evaluated. Routine monitoring of expired tidal volume should be used whenever PEEP is added to an anesthesia circuit.

KEY WORDS. Anesthesia machines. Ventilation: positive end-expiratory pressure; tidal volume. Monitoring: oxygen.

Since its introduction in 1969 [1], positive end-expiratory pressure (PEEP) ventilation has been used in intensive care units to improve arterial oxygenation. Its beneficial effect is thought to be most pronounced in conditions with diminished lung compliance, in which increased functional residual capacity may decrease expiratory shunting. Intraoperative use of PEEP has become common as well. In one patient, we noted that application of as little as 5 cm H_2O PEEP after tracheal aspiration of gastric fluid resulted in a decrease in delivered tidal volume (DTV). Clinical reports corroborated this observation in intensive care volume ventilators and Bain circuits [2]. Therefore, we decided to quantify the ΔDTV/ΔPEEP relationship in two commonly used anesthesia machine systems. The effect of changing pulmonary compliance and PEEP valve location on this relationship was also evaluated.

MATERIAL AND METHODS

The ΔDTV/ΔPEEP relationship was investigated for two common automatic ventilation/circle breathing systems. The first system included a North American Dräger (NAD) (Telford, PA) Model AV ventilator, NAD carbon dioxide absorber, 90 cm of 22-mm corrugated tubing connecting ventilator and absorber, an Intertech/Ohio (Bannockburn, IL) disposable patient breathing circuit, and a NAD Narkomed II anesthesia machine with all NAD 19.1 vaporizers turned off. The second system included an Ohmeda (Madison, WI) Model 7000 ventilator, an Ohmeda GMS absorber, an Intertech/Ohio disposable patient breathing circuit, and an Ohmeda Modulus II anesthesia machine with all Ohmeda Tec 4 vaporizers turned off.

An Ambu (Copenhagen, Denmark) adjustable PEEP

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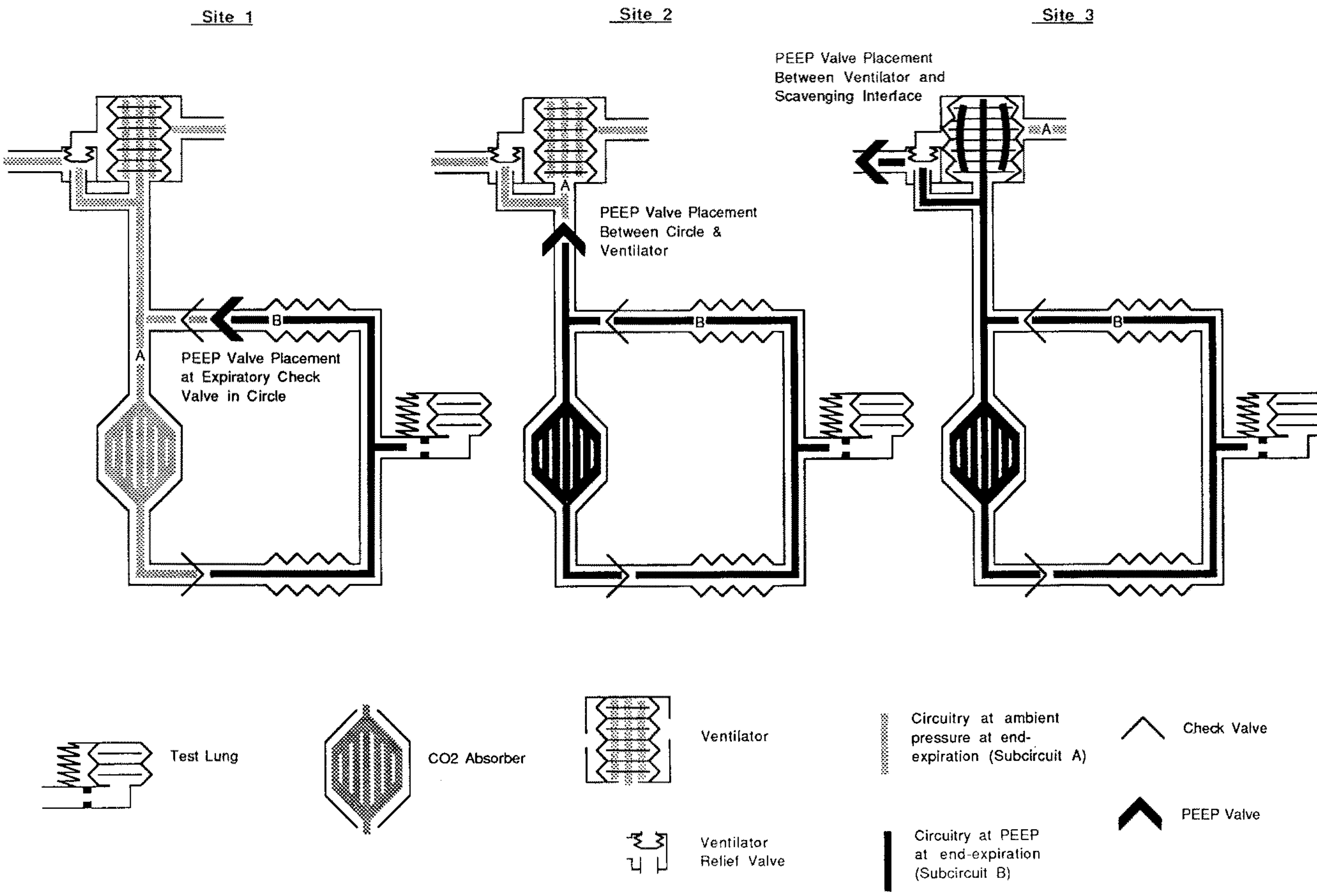

Fig 1. Schematic for breathing circuits studied, showing end-expiratory pressure at various locations. PEEP = *positive-end expiratory pressure.*

valve was used in the investigation of both systems. Figure 1 shows the three PEEP valve placement sites. They are site 1, in the circle; site 2, between the circle and ventilator; and site 3, between the ventilator and the scavenger. The Ambu PEEP valve allows unencumbered reverse gas flow. This attribute, not common to all PEEP valves, was necessary since both inspiratory and expiratory flow traverse site 2.

A Bio-tek Adult Ventilator Tester Model VT-1 (Winooski, VT) provided a pneumatic test load for the system. The VT-1 was adjusted to simulate patient airway resistance with a 5-cm H_2O/L/s parabolic restrictor [3]. Simulated lung compliance was adjusted to 0.01, 0.02, and 0.05 L/cm H_2O. After a 10-breath sample, DTV, end-expiratory pressure, duration of inspiration and expiration, and maximum inspiratory pressure were recorded by the test lung.

Ventilators were set for an inspiratory-expiratory ratio of 1:2 and a respiratory rate of 10 breaths/min. Test gas was 100% oxygen with 4 L/min fresh gas flow. Ventilator tidal volume (VTV) was adjusted to provide DTVs of 300 and 800 ml/breath without PEEP, following the manufacturers' instructions. Because both ventilators are normally used in the volume-limited mode, the only loss of inspiratory volume through relief valves occurred with PEEP valve placement at site 3, as explained in the Discussion section. The NAD ventilator flow setting was adjusted to assure complete vertical bellows excursion while minimizing horizontal bellows deformation. Readjustment was often required when the PEEP level was changed. No adjustments to Ohmeda ventilator settings were required.

RESULTS

The ΔDTV/ΔPEEP relationships for NAD and Ohmeda circuits with measured VTV of 300 ml/breath at three different compliances are plotted in Figure 2. Figure 3 shows ΔDTV/ΔPEEP for the NAD and Ohmeda circuits at measured VTV of 800 ml/breath.

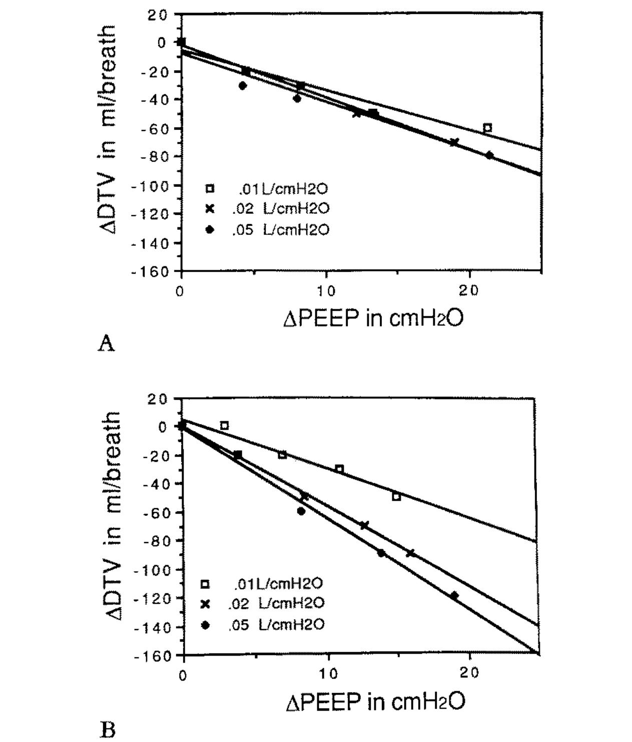

Fig 2. Relationship between a change in delivered tidal volume (ΔDTV) and a change in positive end-expiratory pressure (ΔPEEP) for North American Dräger (A) and Ohmeda (B) ventilatory circuits for various lung compliances, with PEEP valve at site 1 and a measured ventilator tidal volume of 300 ml/min.

Figure 4 shows the effect of PEEP valve location on ΔDTV/ΔPEEP for each of the machines tested.

DISCUSSION

The relationship between PEEP and DTV is a function of VTV, fresh gas volume (FGV), or the volume of gas delivered to the breathing circuit by the anesthesia machine during an individual inspiratory period, and the volume of gas compressed in the ventilatory circuit during the ventilation cycle. Mandatory ventilation without PEEP requires a portion of the gas leaving the ventilator bellows to be expended in elevating breathing circuit pressure. For the two anesthesia ventilation systems studied, assuming no leaks, this relationship can be expressed as:

$$DTV = VTV + FGV - LTV_{cc}, \quad (1)$$

where LTV_{cc} is the portion of tidal volume lost to gas compression and circuit compliance [4,5]. With the addition of PEEP, ventilatory circuit gas compression is required not only to increase pressure from end-

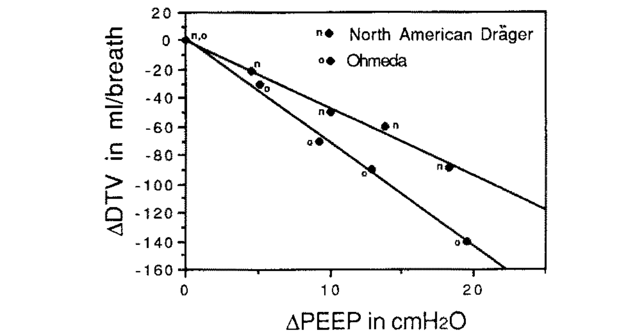

Fig 3. Relationship between a change in delivered tidal volume (ΔDTV) and change in positive end-expiratory pressure (ΔPEEP) for North American Dräger and Ohmeda ventilatory circuits with PEEP valve at site 1. Simulated lung compliance = 0.05 L/cm H_2O; measured ventilator tidal volume = 800 ml/breath.

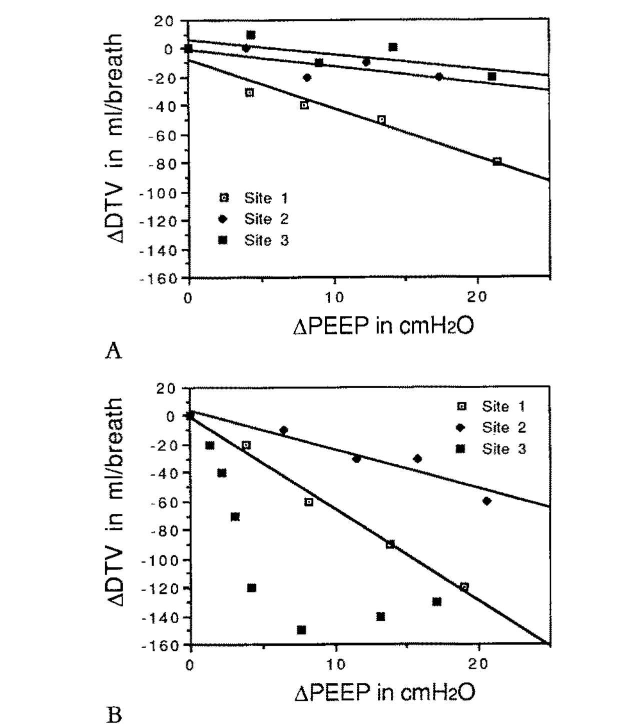

Fig 4. Effect of positive end-expiratory pressure (PEEP) valve site on the relationship between a change in delivered tidal volume (ΔDTV) and a change in PEEP (ΔPEEP) for North American Dräger (A) and Ohmeda (B) ventilatory circuits. Measured ventilator tidal volume = 300 ml/breath; simulated lung compliance = 0.05 L/cm H_2O.

expiratory pressure to peak inspiratory pressure, but also to increase pressure in a portion of the circuit from ambient pressure to PEEP. This portion of the circuit (labeled *Subcircuit A*) is the stippled area in Figure 1. Thus, the inclusion of PEEP results in an additional term in equation 1. This term accounts for the portion of VTV lost bringing ventilatory circuit pressure up to PEEP during the initial inspiratory period before gas is delivered to the patient (LTV_p):

$$DTV = VTV + FGV - LTV_{cc} - LTV_p. \quad (2)$$

It is important here to note that the tidal volume lost, LTV_p, remains constant over a range of VTV values, as is demonstrated by comparing Figures 2 and 3. The clinical corollary to this point is that, as smaller VTVs are selected with LTV_p remaining constant, the ΔDTV becomes more clinically significant.

The ΔDTV/ΔPEEP relationship varies directly with pulmonary compliance. In the patient with stiff lungs, for example, the DTV will decrease minimally with the addition of PEEP, compared to the ΔDTV in the patient with the higher pulmonary compliance. Equation 2 reveals that DTV may be decreased by losses due either to compliance and compression changes (LTV_{cc}) or to PEEP changes (LTV_p). Pulmonary compliance, however, has no influence on LTV_p. LTV_p, as defined, results in tidal volume losses generated before the inspiratory check valve opens, and as LTV_p occurs, the patient's lungs are not connected pneumatically to the ventilator. Thus, variation in ΔDTV/ΔPEEP with a change in patient lung compliance is attributable to LTV_{cc} being affected by a change in PEEP.

To understand the interaction between PEEP and LTV_{cc}, we consider a simple model of LTV_{cc}. In the absence of PEEP, as a linear function of VTV,

$$LTV_{cc} = (VTV + FGV)C_{bc}/C_t, \quad (3)$$

where C_t is the total compliance and compression of the breathing circuit plus patient and C_{bc} is the compliance and compression of the breathing circuit alone. With the addition of PEEP, however,

$$LTV_{cc} = (VTV + FGV - LTV_p)C_{bc}/C_t. \quad (4)$$

Thus, addition of PEEP results in addition of LTV_p with the concomitant reduction in LTV_{cc} by the value of $(LTV_p \times C_{bc})/C_t$. The PEEP effect on LTV_{cc}, therefore, is increased by a decrease in pulmonary compliance. Because varying pulmonary compliance does not affect LTV_p, equation 2 demonstrates that decreased compliance reduces the net volume loss effect on DTV resulting from PEEP. A clinical corollary derived from the ΔDTV/ΔPEEP measurements suggests that the old adage, "a little PEEP can do no harm," is inaccurate. Although this may be partly true for the patient with stiff lungs, the ΔDTV/ΔPEEP losses can be significant in patients with normal compliance. It should be recognized that patient compliance clinically may vary over time and in response to therapeutic maneuvers, including the addition of PEEP.

The portions of the breathing circuit where PEEP and ambient pressures are found during end expiration (subcircuits B and A, respectively) are separated, as shown in Figure 1. The pressure in both subcircuits B and A is approximately equal during most of inspiration. ΔDTV/ΔPEEP is dependent on the volume of gas within subcircuit A, since this is the volume requiring a pressure change from ambient up to peak inspiratory pressure instead of the normal end-expiratory pressure up to peak inspiratory pressure during the initial inspiratory period.

Of the three PEEP valve placement sites tested, site 1 results in the largest subcircuit A and site 3 the smallest, as displayed in Figure 1. Data revealed that, with the exception of site 3 placement on the Ohmeda system, reduction in subcircuit A volume provides less DTV loss. The exception (site 3, Ohmeda) is a consequence of the effect of hyperinflation of the ventilator bellows on ΔDTV/ΔPEEP. Bellows distention or hyperinflation occurs when pressure within the bellows is maintained at PEEP while gas surrounding it is allowed to drop to ambient pressure. As a consequence of the hyperinflation, the initial portion of the inspiratory phase merely brings ventilator cylinder pressure up from ambient to PEEP and returns the bellows to its normal shape. Gas leaving the bellows is exhausted through the relief and PEEP valves until the bellows' driving gas pressure exceeds PEEP. The resulting tidal volume loss increases the magnitude of ΔDTV/ΔPEEP while technically differing from our definition of LTV_p. The pronounced nonlinearity in this relationship is a consequence of the limitation placed on bellows expansion by the ventilator cylinder.

Expiratory bellows hyperinflation occurs with site 3 placement in the NAD breathing system as well. With this system, ΔDTV/ΔPEEP is not significantly influenced by the occurrence, however, since normal operation of the device calls for operator compensation for changes resulting in incomplete bellows excursion. That is, the operator manual indicates that the "flow setting should be adjusted so that the bellows is fully compressed at the end of the inspiratory phase." This flow setting adjustment offsets the effect that gas lost through the relief valve during initial inspiratory period has on DTV.

SUMMARY

A PEEP valve in a controlled mechanical ventilatory circuit decreases DTV. Reduction in DTV is primarily a function of circuit configuration and becomes increasingly significant for tidal volumes of decreasing magnitude. In general, ventilatory circuit design can reduce ΔDTV/ΔPEEP by relocating the PEEP valve to increase circuit volume maintained at PEEP during end expiration. Ventilatory circuits should be evaluated, however, to determine specific design influence on this relationship. Decreased pulmonary compliance decreases the magnitude of ΔDTV/ΔPEEP. Routine monitoring of expired tidal volume can reveal the magnitude of the effect of ΔPEEP on DTV and assure that the desired volume is maintained.

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