# Tidal volumes for ventilated patients should be determined at the endotracheal tube

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*Exhaled tidal volume (VTE) in ventilated patients is most accurately measured at the patient airway opening, concludes various studies. These studies, which compare VTE measured at the patient airway and VTE measured distal to the patient airway—with or without compensation for breathing circuit compliance—demonstrate significantly increased measurement accuracy when measurements are made at the patient airway.*

## Introduction

Accurate determination of exhaled tidal volume (VTE) is important, especially in situations where small tidal volumes are delivered (infants and neonates, ARDS patients).

Most critical care ventilators measure VTE distal to the patient, i.e., inside the device itself, close to the expiratory valve. A few, such as HAMILTON MEDICAL ventilators, measure VTE close to the patient airway. Over the past years, studies have assessed the accuracy of VTE measurements. These studies conclude that measurements distal to the patient—even when compensated for circuit compliance—do not determine VTE with sufficient clinical accuracy. Instead, the studies conclude that accurate VTE values can be reliably obtained only at the patient airway.

The studies show the differences between VTE values from these two measurement sites to be especially great when infant and pediatric patients are ventilated, especially infants with high airway impedance and infant/pediatric patients with uncuffed and therefore leaky endotracheal (ET) tubes.

## How ventilators determine VTE

Critical care ventilators determine VTE using one of the following methods (Figure 1):

- Measurement distal to the patient with a flow sensor in the expiratory limb (in this paper to be called in-ventilator measurement)
- Measurement distal to the patient with a flow sensor in the expiratory limb, with the measured VTE corrected for breathing circuit compliance (in this paper to be called calculated VTE)
- Measurement with a flow sensor at the patient airway between the Y-piece and the ET tube (in this paper to be called patient airway measurement)

## Potential advantages

In theory the closer the flow sensor is placed to the patient, the more accurately the ventilator can determine the patient's VTE. Placing the flow sensor close to the patient eliminates the effects of breathing circuit compliance on flow and volume measurements—that is, the extent to which a change of pressure changes volume. The rationale for monitoring VTE in the expiratory limb rather than at the airway is that water vapor, exudate, blood, many sources of artefacts, and handling problems challenge patient airway measurements.[1] The drawback to these in-ventilator measurements is that their accuracy is degraded by leaks in the patient tubing and the compliance of the patient tubing. Adding a humidifier further affects compliance.

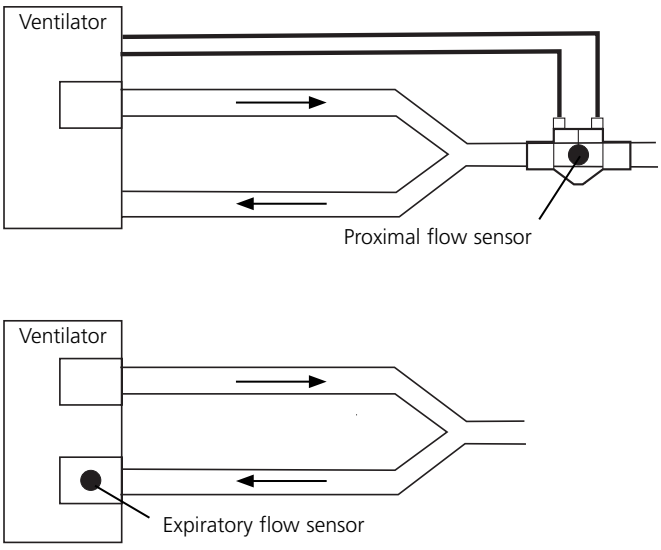


Figure 1. The two flow sensing locations in critical care ventilators

Theoretically, a compensation formula can be used to minimize the effects of circuit compliance.[2] Calculated VTE can be defined as the in-ventilator VTE minus the compressible volume (shown in Figure 2) lost due to the breathing circuit compliance, as follows:

$$VTE_{calculated} = VTE_{in\text{-}ventilator} - C_{circuit} \times (PIP - PEEP)$$

Figure 2. Compressible volume. The gray area represents the additional volume attributable to patient circuit compliance. Compliance compensation equations subtract this volume to produce the calculated VTE.

Practically speaking, however, satisfactorily compensating the VTE can be difficult. For example, tubing compliance may change over time as water vapor condenses and connectors develop small leaks. Moreover, variations in the breathing circuit setup (i.e., heaters, humidifiers, water traps, in-line suction devices, and other devices) are not included in such a calculation.

For these reasons, patient airway flow sensing provides the most accurate results, assuming certain preconditions are met, including the correct positioning of flow sensing tubes, continuous flushing of tubes to prevent condensation, and appropriate inner diameter and length of the sensing tubes.[1]

## Evidence

Several studies over the past years have examined VTE accuracy based on its method of determination, circuit and lung compliance, and ET tube leakage (Table 1).

### Method of VTE determination may significantly affect VTE accuracy in smaller patients

In a study by Cannon et al., 98 infant and pediatric patients were ventilated with Siemens Servo 300 ventilators in pressure- and volume-controlled modes.[2] The reference VTE values obtained from a pneumotachograph placed close to the patient were compared with in-ventilator and calculated VTE values. Results are as shown in Figure 3.

For infant patients, reference VTE was significantly less than either the in-ventilator or calculated VTE. Clearly, correcting for breathing circuit compliance did not reduce this discrepancy.

The paper concludes that for infants, VTE should be determined with a pneumotachometer placed at the patient airway.

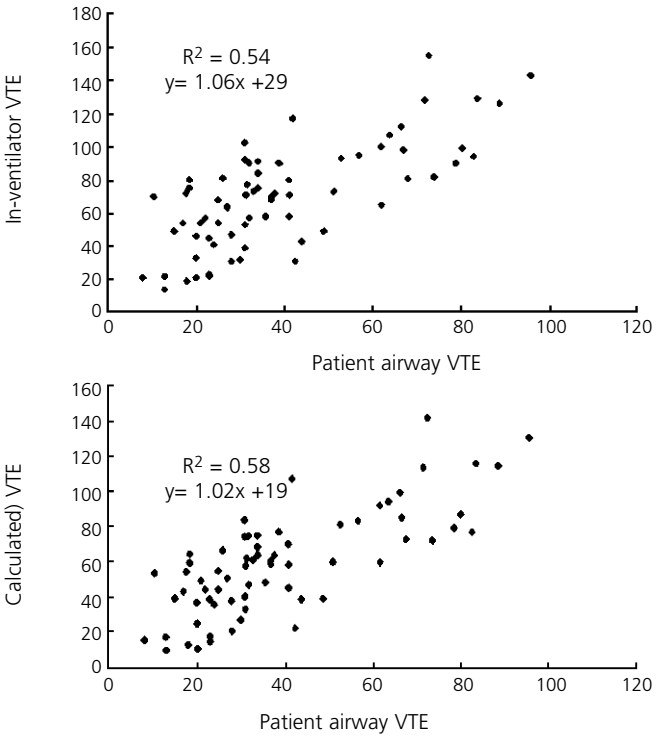


Figure 3. Tidal volume comparisons for neonatal circuit (top). Regression analysis for in-ventilator VTE versus patient airway VTE (bottom). Regression analysis for calculated VTE versus patient airway VTE. (Cannon)

Yet another study by Castle et al. involving 56 pediatric patients assessed the accuracy of in-ventilator and calculated VTE, again by comparing these against reference values from a pneumotachograph near the patient.[3] These patients were ventilated on Siemens 300 ventilators.

This study concluded that VTE accuracy is crucially dependent on the measurement site. Displayed values not measured at the airway opening are an inconsistent and misleading indicator of the true volumes delivered.

### Increased respiratory system impedance may impact VTE

A study by Nève et al. assessed VTE accuracy for 30 infants with increased respiratory system impedance.[4] The infants were ventilated on Servo 300 ventilators in pressure- or volume-controlled modes. Reference patient airway VTE was compared with in-ventilator and calculated VTE. As resistance of the respiratory system increased, the difference between reference values and the values displayed by the ventilator increased (Figure 4).

In another study, Gammage et al. found that at normal compliance, there was no clinically significant difference between reference VTE and the VTE values displayed by the ventilator, but that at low compliance, only the GALILEO ventilator displayed clinically accurate VTE values.

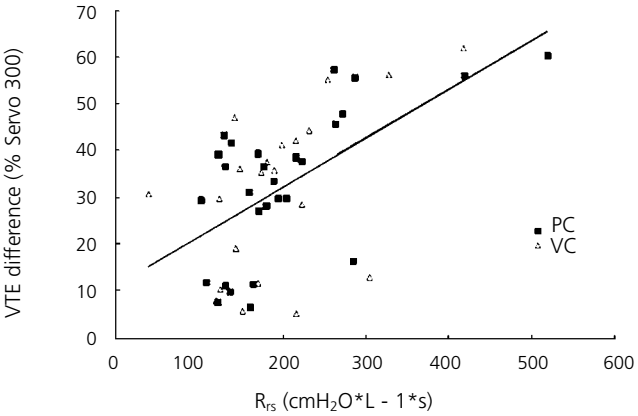


Figure 4. Relationship between relative VTE difference (percentage of VTE displayed by the Servo 300) and the respiratory system resistance ($R_{rs}$). PC = pressure controlled. VC = volume controlled. (Nève)

## ET tube leaks may adversely affect VTE measurements, even when measurements are compliance compensated

Al-Majed et al. examined how VTE accuracy is affected by ET tube leakage[6] and found that calculated VTE overestimated reference VTE by at least 0.6 ml/kg or 10%, and even more as leakage increased.

The study concluded that when there is ET tube leakage, calculated VTE is inaccurate and VTE is most accurately estimated at the airway.

## GALILEO's displayed VTE remains accurate under resistance and leakage conditions

A recent study examined the accuracy of the GALILEO's displayed VTE under a range of resistance and leakage conditions.[7] Measurements displayed by the GALILEO (based on a proximal flow sensor) were compared with reference measurements made by a pneumotachograph and Michigan test lung. Measurements were made using a range of ventilation modes.

The GALILEO's VTE measurements were closely correlated with the reference measurements, even in situations of high resistance (up to 40 $cmH_2O$/ml/s) (Figure 5).

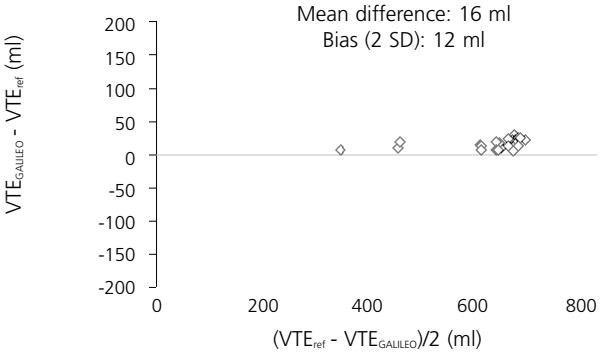


Figure 5. VTE displayed by the GALILEO is highly correlated with the reference VTE. The Bland and Altman analysis found that the mean difference between the displayed and reference VTEs was 16 ml with a bias of 12 ml. Values were obtained with different ventilation modes and different respiratory mechanics (from 0 to 40 $cmH_2O$/l/s of airway resistance).

**Table 1. Summary of studies assessing VTE accuracy**

| Study | Patient type | No. of participants | Equipment | Conclusions |
|---|---|---|---|---|
| Cannon[2] | Infant/pediatric | 98 | Siemens Servo 300 ventilator | For infants, VTE should be determined by a pneumotachometer placed at the airway. |
| Castle[3] | Infant/pediatric | 56 | Siemens Servo 300 ventilator | VTE values not measured at the airway opening are an inconsistent and misleading indicator of the true volumes delivered. |
| Nève[4] | Infants | 30 | Siemens Servo 300 ventilator | Correcting VTE for circuit compliance cannot replace measurement of VTE at the Y-piece. |
| Gammage[5] | Adult test lung | -- | Major critical care ventilators | Only the HAMILTON MEDICAL ventilator displayed accurate VTE values compared with reference. |
| Al-Majed[6] | Infant/pediatric/adult lung models | -- | Siemens Servo 300 ventilator | It is safest to measure VTE at the airway in all mechanically ventilated children. |
| Volzer[7] | Infant/pediatric/adult lung models | -- | HAMILTON MEDICAL GALILEO ventilator | The GALILEO ventilator displayed accurate VTE values even under resistance and leakage conditions. |

The GALILEO's VTE accuracy was also tested in in the presence of leaks (from 10 to 50% of the inspired tidal volume). Again, the GALILEO's VTE measurements approximated the reference measurements (Figure 6).

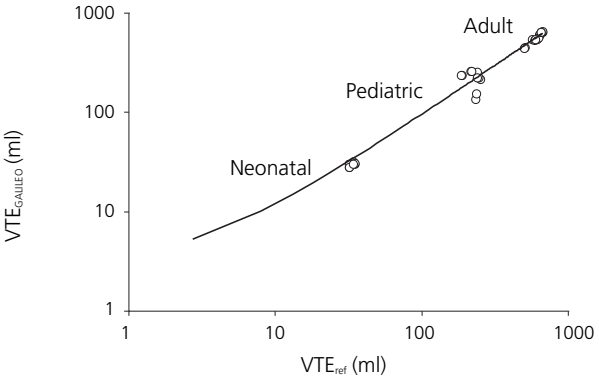


Figure 6. VTE displayed by the GALILEO in presence of 10, 25, and 50% leaks as compared to reference VTE. In neonatal, pediatric, and adult patients the GALILEO displayed accurate data even in the presence of leaks. (Volzer)

## Conclusion

For accurate VTE values, all the available studies support flow sensing at the patient airway, which is implemented in HAMILTON MEDICAL ventilators. All confirm clinically significant inaccuracies in in-ventilator and calculated VTE values. This is especially so in infant and pediatric patients, and in patients with ET tube leakage and low lung compliance and/or resistance.

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