Breathing circuit compliance and accuracy of displayed tidal volume during pressure-controlled ventilation of infants: A quality improvement project

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Summary

Introduction: Anesthesia machines have evolved to deliver desired tidal volumes more accurately by measuring breathing circuit compliance during a preuse self-test and then incorporating the compliance value when calculating expired tidal volume. The initial compliance value is utilized in tidal volume calculation regardless of whether the actual compliance of the breathing circuit changes during a case, as happens when corrugated circuit tubing is manually expanded after the preuse self-test but before patient use. We noticed that the anesthesia machine preuse self-test was usually performed on nonexpanded pediatric circuit tubing, and then the breathing circuit was subsequently expanded for clinical use. We aimed to demonstrate that performing the preuse self-test in that manner could lead to incorrectly displayed tidal volume on the anesthesia machine monitor. The goal of this quality improvement project was to change the usual practice and improve the accuracy of displayed tidal volume in infants undergoing general anesthesia.

Methods: There were four stages of the project: (i) gathering baseline data about the performance of the preuse self-test and using infant and adult test lungs to measure discrepancies of displayed tidal volumes when breathing circuit compliance was changed after the initial preuse self-test; (ii) gathering clinical data during pressure-controlled ventilation comparing anesthesia machine displayed tidal volume with actual spirometry tidal volume in patients less than 10 kg before (machine preuse self-test performed while the breathing circuit was nonexpanded) and after an intervention (machine preuse self-test performed after the breathing circuit was fully expanded); (iii) performing department-wide education to help implement practice change; (iv) gathering postintervention data to determine the prevalence of proper machine preuse self-test.

Results: At constant pressure-controlled ventilation through fully expanded circuit tubing, displayed tidal volume was 83% greater in the infant test lung (mean±SD TV 15±5 vs 9±4 mL; mean [95% CI] difference=6.3 [5.6, 7.1] mL, P<.0001) and 3% greater in the adult test lung (245±74 vs 241±72 mL; difference=5 [1, 10] mL, P=.0905) when circuit compliance had been measured with nonexpanded tubing compared to when circuit compliance was measured with fully expanded tubing. The clinical data in infants demonstrated that displayed tidal volume was 41% greater than actual tidal volume (difference of 10.4 [8.6, 12.2] mL) when the circuit was expanded after the preuse self-test (preintervention) and 7% greater (difference...
of 2.5 [0.7, 4.2] mL) in subjects when the circuit was expanded prior to the preuse self-test (postintervention) (P<.0001). Clinical practice was changed following an intervention of departmental education: the preuse self-test was performed on expanded circuit tubing 11% of the time prior to the intervention and 100% following the intervention.

**Conclusion:** Performing a preuse self-test on a nonexpanded pediatric circuit that is then expanded leads to falsely elevated displayed tidal volume in infants less than 10 kg during pressure-controlled ventilation. Overestimation of reported tidal volume can be avoided by expanding the breathing circuit tubing to the length which will be used during a case prior to performing the anesthesia machine preuse self-test. After department-wide education and implementation, performing a correct preuse self-test is now the standard practice in our cardiac operating rooms.

**KEYWORDS**
anesthesia machine, circuit compliance, infant, pressure-controlled ventilation

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1 | **INTRODUCTION**

1.1 | **Problem Description**

Anesthesia machines have evolved to deliver more accurate tidal volume (TV) by calculating and incorporating breathing circuit compliance. The circuit compliance is measured automatically during the electronic preuse self-test and is subsequently used for the remainder of the case regardless of whether the actual compliance of the breathing circuit changes. Changes in displayed TV may arise when compliance is measured before patient use on a nonexpanded (as delivered by the manufacturer) breathing circuit that is subsequently expanded for clinical use, as a nonexpanded circuit is less compliant than an expanded circuit. An anesthesia machine that utilizes circuit compliance may report incorrect TV if the breathing circuit compliance changes after the initial preuse self-test.

We noticed that the preuse self-test was frequently performed using nonexpanded breathing circuits. The aim of this quality improvement project was to determine whether displayed TV differed from delivered TV when the preuse self-test was performed with nonexpanded vs expanded breathing circuits and, if so, whether an intervention would result in more accurate displayed TV. We report the results of this project following the revised Standards for Quality Improvement Reporting Excellence (SQUIRE).  

1.2 | **Available knowledge**

Mechanical ventilation in the infant patient has long been acknowledged to be a challenging endeavor. As infants require much smaller TV than adults, small changes in TV or airway pressures can have significant effects on minute ventilation and risk of suboptimal ventilation or lung damage. When utilizing mechanical ventilation on an infant, it is imperative to avoid volutrauma and barotrauma, as well as extremes in hyper- and hypoventilation. Volutrauma is caused by excessively high TV which leads to over distention of alveoli, and excessively high peak pressure can lead to barotrauma. Low TV is not associated with lung injury during mechanical ventilation, but excessively low TV may cause other problems such as hypoventilation and elevated PCO2. Clearly, it is imperative that the TV displayed on the anesthesia machine monitor accurately reflects the delivered TV, especially in the infant population, to ensure adequate ventilation.

During the electronic preuse self-test of modern anesthesia machines, the external compliance is calculated by the machine. The
external compliance includes the compliance of the breathing circuit in addition to the mechanical components of the ventilator. The compliance of the breathing circuit is defined as the change in volume of the circuit during a change in delivered pressure by the ventilator, and is measured in mL/cm H₂O. This compliance can affect the amount of TV delivered to the patient and displayed by the machine if it is not accounted for. During volume-controlled ventilation (VCV), delivered TV was up to 55% less than set TV in the absence of circuit compliance calculation. Compliance compensation is utilized by the ventilator to help guarantee a set TV to the patient in VCV mode. By compensating for the compliance of the circuit, the ventilator delivers extra volume on each breath by calculating how much volume is lost to the compliance of the breathing circuit. The delivered TV to the patient may be calculated using the following equation:

\[
V^{(T)} = V^{(TV)} - C^{(bc)} \cdot (\text{PIP} - \text{PEEP})
\]

In this equation, \(V^{(T)}\) is actual TV delivered to the patient, \(V^{(TV)}\) is TV delivered by the ventilator, \(C^{(bc)}\) is calculated compliance of breathing circuit, PIP is peak inspiratory pressure, and PEEP is end-expiratory pressure.

In the pressure-controlled ventilation (PCV) mode of mechanical ventilation, compliance compensation is also utilized. Delivering the set inspiratory pressure as quickly as possible is a goal of PCV, and the compliance of the breathing circuit can affect this. In PCV, as the pressure in the system increases, the flow rate decreases. This decelerating flow is a core characteristic of PCV and affects the TV delivered to the patient. Thus, if the compliance of the breathing circuit is very low, the pressure in the system will build more quickly and the flow rate will decrease earlier than if the breathing circuit compliance were higher. With compliance compensation, the circuit compliance is taken into account and more appropriate peak pressure and flow are applied to the patient, and thus more precise TV is delivered as well. The newer anesthesia machines also have eliminated the association between the amount of fresh gas flow and delivered TV.

1.3 | Rationale

The caveat to compliance compensation is that the anesthesia machine uses the circuit compliance that is initially calculated during the entire case, regardless of whether the compliance of the breathing circuit changes in the interim. This can occur when the anesthesia machine self-test precheck is performed on nonexpanded (as delivered from the manufacturer) pediatric circuit tubing, and then the breathing circuit is subsequently expanded for clinical use. We believed that using an expanded breathing circuit following a compliance calculation on a nonexpanded would cause a discrepancy between displayed and actual TV, especially in infants.

1.4 | Specific aim

The aim of this quality improvement project was to improve the accuracy of displayed TV in infants undergoing general anesthesia at our hospital. This goal was to be achieved by completing two Plan-Do-Study-Act (PDSA) cycles to demonstrate that a proper anesthesia machine preuse self-test could reduce the discrepancy between displayed and actual TV, and that implementing a new standard of practice through education of a proper machine check could improve the accuracy of displayed TV.

2 | MATERIALS AND METHODS

2.1 | Context

This quality improvement initiative was performed in the cardiac operating suite at Children’s Hospital Colorado and was approved by the Organizational Research Risk & Quality Improvement Review Panel (ORRRQRP), which waived the requirement for individual informed consent. The cardiac operating suite serves approximately 1500 patients annually and consists of five anesthetizing locations: two cardiac surgical operating rooms, two cardiac catheterization labs, and one room for anesthetized echocardiography and minor procedures. Anesthesia machines that calculate and incorporate circuit compliance when delivering patient breaths were utilized. There were four main stages of this Plan-Do-Study-Act (PDSA) project.

2.2 | Baseline data (Stage 1)

In a bench study of 4 Dräger Apollo (Drägerwerk, Lübeck, Germany), 10 GE S5 Avance (GE Healthcare, Wisconsin, USA), and 3 GE Aisys anesthesia machines, the preuse self-test was performed while connected to a nonexpanded (as delivered from the manufacturer) pediatric breathing circuit (Westmed, Arizona, USA). The breathing circuit was then fully expanded and connected to an infant or adult test lung (Maquet models 190/191, Siemens, Germany), which was ventilated in the PCV mode at pressure settings of 18/4, rate of 24 ( Infant or 15 (adult), and I:E ratio 1:2. Fresh gas was air and oxygen at a flow rate of 5 L/min, and FiO₂ was 0.5. Displayed expired TV was recorded. The anesthesia machine was restarted and the preuse self-test was subsequently performed while connected to the fully expanded circuit. Displayed expired TV was then re-recorded using the same ventilator settings. Each anesthesia machine was tested three times with both infant and adult test lungs. Figure 1 summarizes the methods used in this portion of the project. Data were analyzed with analysis of variance and paired t-tests.

The frequency of performance of the preuse self-test using expanded or nonexpanded circuit tubing was observed in the cardiac suite during a 2-week period (the last 2 weeks of July 2015).

2.3 | Clinical data and intervention (Stage 2)

Using four different Dräger Apollo anesthesia machines, the preuse self-test was performed while connected to a nonexpanded (as delivered) pediatric breathing circuit (Neonatal 1F-LF, Medline, Illinois, USA) that was then subsequently fully expanded for use in infants weighing less than 10 kg undergoing general anesthesia in the
cardiac operating suite. While under general anesthesia, PCV was maintained in a stable state with endtidal PCO2 35-40 mmHg. Fresh gas (oxygen and air) flow rate was 2 L/min, and FiO2 ranged from 0.25 to 0.4 depending on clinical needs. Expired TV was simultaneously recorded from the anesthesia machine display and from an electronic spirometer (NICO, Novametrix, Connecticut, USA) attached to the expiratory limb at the Y of the breathing circuit. Five measurements were made and averaged in each of 12 subjects. This was our preintervention group.

The intervention consisted of performing the preuse self-test following complete expansion of the breathing circuit prior to the preuse self-test. Our postintervention group consisted of 12 additional infants each weighing less than 10 kg. For the postintervention group, expired TV was recorded from the anesthesia machine display and an electronic spirometer during stable PCV as described above. Differences between TV measured by the spirometer and displayed on the anesthesia machine were analyzed with paired t-tests.

2.4 | Education and implementation (Stage 3)

All of the anesthesia technicians and anesthesia providers in the cardiac operating rooms were educated as to how to properly perform the preuse self-test. This was achieved both through small group discussions and a department-wide conference presentation. Both baseline and clinical data were presented, and it was highlighted that the breathing circuit tubing should be expanded to an appropriate length prior to performing the preuse self-test.

2.5 | Follow-up (Stage 4)

After the education and implementation of the proper way to perform a preuse self-test, the frequency of performance of the preuse self-check using expanded or nonexpanded circuit tubing was observed in the cardiac suite during a 2-week period (the last 2 weeks in July 2016).

3 | RESULTS

3.1 | Baseline data (Stage 1)

The displayed TV was significantly greater for the infant test lung when PCV was delivered through circuit tubing that was expanded after the circuit compliance calculation than when delivered through tubing that was expanded before the compliance calculation (mean±SD 15±5 vs 9±4 mL; mean [95% CI] difference=6.3 [5.6, 7.1] mL, P<.0001 by paired t-test) (Table 1). The displayed TV was not significantly different in the adult test lung when delivered following either nonexpanded or expanded circuit compliance test (245±74 vs 241±72 mL; difference=5 [1, 10] mL, P=.905 by paired t-test) (Table 1). The mean discrepancy in displayed TV for the

![FIGURE 1](Image 75x745 to 121x754) Testing sequence on infant and adult test lungs

| TABLE 1 | Changes in circuit compliance and displayed tidal volume measurements in infant and adult test lungs during pressure-controlled ventilation at 18/4 cm H2O when the anesthesia machine preuse self-test was performed before and after circuit tubing expansion |
| --- | --- | --- | --- | --- |
| Machine | Drager Apollo (n=4) | GE Avance S5 (n=10) | GE Aisys (n=4) | All Combined (n=18) |
| Compliancea (mL/cm H2O) | 0.43±0.05 | 0.45±0.07 | 0.47±0.07 | 0.45±0.07 |
| Complianceb (mL/cm H2O) | 0.97±0.05 | 0.92±0.10 | 0.95±0.07 | 0.94±0.09 |
| Infant TVc (mL) | 14±5 | 15±3 | 19±6 | 15±5 |
| Infant TVd (mL) | 8±2 | 8±3 | 12±5 | 9±4 |
| Adult TVc (mL) | 246±11 | 234±92 | 284±14 | 245±74 |
| Adult TVd (mL) | 249±18 | 227±89 | 278±15 | 241±72 |

Data are expressed in mean±SD. GE, GE Healthcare; TV, displayed expired tidal volume.
aCircuit tubing not expanded.
bCircuit tubing fully expanded.
cTubing not expanded for preuse self-test, then expanded for TV measurement.
dTubing expanded for preuse self-test, remained expanded for TV measurement. Intermachine differences were not significant by analysis of variance.

Values of compliance and infant test lung TV between conditions were significantly different by paired t-test. Values of adult test lung TV between conditions were not significantly different by paired t-test.
infant test lung was 83% compared to 3% for the adult test lung (Figure 2).

Nonexpanded breathing circuits were used for the preuse self-check in 64 of 72 (89%) cases in the cardiac operating suite during the 2-week period.

### 3.2 Clinical data and intervention (Stage 2)

The data for the pre- and postintervention patient groups are displayed in Table 2. Compliance of the expanded circuit was about twice that of the nonexpanded circuit. The mean ± SD discrepancy between TV displayed on the anesthesia machine monitor and TV measured by the spirometer was 10.4 ± 3.4 mL when the breathing circuit was expanded after the preuse self-test compared to 2.5 ± 2.5 mL when the breathing circuit was expanded before the preuse self-test. The mean [95% CI] difference in discrepancies between the two conditions was 7.9 [5.4, 10.4] mL (P < .0001 by one-way analysis of variance). The mean percentage discrepancy (increase) in TV displayed on the anesthesia machine vs the electronic spirometer was 41% for the subjects in the preintervention group and 7% for the postintervention group (Figure 3).

In Figure 4, the percentage overestimation of TV from the anesthesia machine display vs the electronic spirometer is shown for each subject. This run chart demonstrates the improvement in the accuracy of displayed TV after the intervention.

<table>
<thead>
<tr>
<th>Patient weight (kg)</th>
<th>Circuit Compliance (mL/cm H₂O)</th>
<th>Displayed TV (mL)</th>
<th>Spirometry TV (mL)</th>
<th>TV difference (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preintervention (n=12)</td>
<td>4.3 ± 1.4</td>
<td>0.37 ± 0.05</td>
<td>39 ± 18</td>
<td>28 ± 16</td>
</tr>
<tr>
<td>Postintervention (n=12)</td>
<td>4.7 ± 2.0</td>
<td>0.85 ± 0.10</td>
<td>43 ± 21</td>
<td>41 ± 19</td>
</tr>
<tr>
<td>Mean difference [95% CI]</td>
<td>0.5 [-1.0, 2.0]</td>
<td>0.48 [0.41, 0.55]</td>
<td>4 [-12, 20]</td>
<td>12 [-3, 26]</td>
</tr>
<tr>
<td>P value</td>
<td>.5043</td>
<td>&lt;.0001</td>
<td>.6274</td>
<td>.0587</td>
</tr>
</tbody>
</table>

Data are displayed as mean ± SD. PCV, pressure-controlled ventilation. TV, expired tidal volume. Pre- and postintervention values were compared with one way analysis of variance (P values displayed).

3.3 Follow-up (Stage 4)

Following the intervention, nonexpanded breathing circuits were used for the preuse self-test in 0 of 68 cases in the cardiac operating suite during the 2-week period.

4 DISCUSSION

This project resulted in improved performance of a proper preuse self-test that was associated with improved accuracy of the TV values displayed on the anesthesia machine monitor. Both the test lung data and the clinical data demonstrated that performing a preuse self-test on a nonexpanded pediatric circuit that is then expanded for clinical use leads to falsely elevated displayed TV in infants less than 10 kg during PCV. This can be avoided by expanding the breathing circuit tubing to the length which will be used during a case prior to performing the anesthesia machine preuse self-test. This intervention significantly decreased the anesthesia machine’s overestimation of delivered TV.

Modern anesthesia machines and ventilators are designed to deliver more accurate TV by compensating for circuit compliance.1,2,9
Our data are consistent with a previous study of VCV of test lungs with small TV, which demonstrated that both the absence of circuit compliance compensation and changes in circuit tubing compliance following the preuse self-test resulted in discrepancies between delivered and displayed TV.7

Lack of knowledge of how newer anesthesia machines incorporate breathing circuit compliance into delivering patient breaths was the main reason why the preuse self-test was usually not performed properly. Once education was provided, the implementation of this project was straightforward and the standard practice was changed almost immediately. Ease of implementation was clearly a strength that facilitated the success of this project at our hospital.

Our project demonstrated that changing the length of expandable anesthesia breathing circuits results in significant changes in circuit compliance that will affect the accuracy of displayed TV. Of course, if nonexpandable circuits are used, this problem may not be encountered, with the caveat that adding additional nonexpandable tubing to achieve greater circuit length may alter the compliance of the circuit.

A limitation of this project was that the clinical data collection and the focus of the implementation portion of the project were limited to the cardiac operating suite. In our hospital, the cardiac operating suite has fewer and separate anesthesia technicians and anesthesia providers when compared to the greater number of general operating rooms. Nevertheless, education was delivered to the entire department, and implementation of the intervention as standard practice in our cardiac operating suite has been successful.

5 | CONCLUSION

The anesthesia machine assumes that circuit compliance remains constant in its calculations of expired TV, but when breathing circuit tubing is manually expanded, the circuit compliance increases and alters the displayed TV. Our data demonstrated that performing a preuse self-test on a nonexpanded pediatric circuit that is then expanded leads to falsely elevated displayed TV in infants less than 10 kg during PCV. Our intervention demonstrated that the overestimation of displayed TV can be avoided by expanding the breathing circuit tubing to the length which will be used during a case prior to performing the anesthesia machine preuse self-test. Simply attaching a nonexpanded circuit to the anesthesia machine and then performing the preuse self-test is insufficient and can potentially be harmful to the patient if the displayed TV is relied on to guide ventilator settings. This quality improvement project has resulted in more accurately displayed TV in infants. After department-wide education and implementation, performing a correct preuse self-test is now the standard practice in our cardiac operating rooms.

CONFLICT OF INTEREST

Robert H. Friesen is Chair of the Editorial Board of Pediatric Anesthesia. The other authors report no conflicts of interest.

ETHICAL APPROVAL

Ethics approval was granted by the Organizational Research Risk & Quality Improvement Review Panel of Children’s Hospital Colorado, Denver, USA.

REFERENCES

