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Please cite this article as https://doi.org/10.4097/kja.20518
1. **A comparison of the breathing apparatus deadspace associated with a supraglottic airway and endotracheal tube using volumetric capnography in young children**

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3. **Running title:** Airway deadspace in children, air-Q vs ETT

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5. **Previous Presentation:** This data was presented on October 20, 2019 at Anesthesiology 2019 in Orlando, Florida, USA at the FAER research symposium for young investigators.

6. **Conflict of Interest:** The authors declare no conflict of interest.

7. **Funding:** Funded by the Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA
8. **Acknowledgements:** N/A

9. **IRB#:** 00055260

10. **ClinicalTrials.gov trial number:** NCT03785977
A comparison of the breathing apparatus deadspace associated with a supraglottic airway and endotracheal tube using volumetric capnography in young children

Running title: Airway deadspace in children, air-Q vs ETT
Abstract

Background: Supraglottic airway devices including the air-Q® are being used with increasing frequency for elective anesthetics in infants and younger pediatric patients. To date, there is minimal research documenting the potentially significant airway dead space these devices may contribute to the ventilation circuit when compared to an endotracheal tube (ETT).

Methods: In a prospective cohort study, 59 pediatric patients between the ages of 3 months and 6 years, weighing between 5 and 20 kg, and scheduled for outpatient urologic or general surgery procedures were recruited. An air-Q® or ETT was inserted at the discretion of the attending anesthesiologist, and tidal volume, respiratory rate, and end-tidal CO₂ were controlled according to protocol. Ventilatory parameters including airway dead space were recorded or calculated using volumetric capnography every two minutes for 10 minutes.

Results: Groups were similar in demographics. There was a significant difference in weight-adjusted dead space volume between the air-Q® and ETT groups, 4.1 ± 0.8 mL/kg versus 3.0 ± 0.7 mL/kg, respectively (p<0.0001). Weight-adjusted dead space volume (in mL/kg) increased significantly with decreasing weight for both the air-Q® and ETT groups.

Conclusion: In healthy children undergoing positive pressure ventilation for elective surgery, the air-Q® supraglottic airway introduces significantly greater airway dead space than an endotracheal tube. Additionally, airway dead space, and minute ventilation required to maintain normocarbia, appear to increase with decreasing patient weight irrespective of whether a supraglottic airway or endotracheal tube is used.

Keywords: Supraglottic airway, laryngeal mask airway, deadspace, ventilation, volumetric capnography, air-Q®
Introduction

Supraglottic airway (SGA) devices including the air-Q® (Cookgas, St. Louis, MO) are being used with increasing frequency for elective anesthetics in infants and younger pediatric patients [1,2]. Although SGAs are presumed to contribute greater deadspace volume to the ventilation circuit when compared to endotracheal tubes (ETT), there has been minimal research that quantifies that difference. This information is relevant in very young patients breathing spontaneously through these devices, who may be unable to generate sufficient tidal volumes to compensate for this added deadspace over time, and in those undergoing positive pressure ventilation who may require increasing levels of support to maintain adequate levels of ventilation [3,4].

Volumetric capnography is a technique that can be used to accurately evaluate airway deadspace by monitoring the concentration of exhaled carbon dioxide (CO₂) over the course of a respiratory cycle [5]. Exhaled CO₂ is plotted against exhaled volume, and from the resulting waveforms, alveolar partial pressure of carbon dioxide (PₐCO₂) and mean exhaled partial pressure of carbon dioxide (PₑCO₂) can be calculated and used to determine airway deadspace [6]. Compared to prior methods that require use of a Douglas bag or calorimetry, volumetric capnography is faster, less cumbersome, and more easily applied clinically [7]. With this technology, it is thus possible to measure the apparatus and airway deadspace noninvasively and in real time.

The primary aim of this study was to compare the magnitude of the airway and apparatus deadspace associated with the use of an ETT or air-Q® SGA using volumetric capnography in young children undergoing general anesthesia and surgery. Additionally, our primary hypothesis was that airway and apparatus deadspace, normalized by weight, is significantly higher in young infants and children when using an air-Q® SGA when compared to the airway and apparatus deadspace associated
with an ETT. Our null hypothesis was that there is no difference in deadspace volume between devices.
Materials and Methods

Patient Selection

This study was approved by the institutional review board at the Wake Forest University Health Sciences (IRB00055260) and was registered on ClinicalTrials.gov prior to beginning recruitment (NCT03785977; 12/24/2018; PI-Templeton TW). Written informed consent from a parent/legal guardian was obtained for participation in this study. This manuscript adheres to the applicable Transparent Reporting of Evaluations with Nonrandomized Designs (TREND) guidelines.

Pediatric patients between the ages of 3 months and 6 years, weighing between 5 and 20 kg, and scheduled for outpatient urologic or general surgery procedures, were identified for participation in the preoperative holding area. All procedures were performed in the pediatric operating room at Brenner Children’s Hospital, Wake Forest Baptist Medical Center from March 2019 to August 2019. Exclusion criteria included: patients with a history of difficult airway/intubation (defined as greater than two attempts at intubation or having required any unanticipated or secondary intubating technique other than direct or elective video laryngoscopy in the past) or those suspected to have a difficult airway; morbid obesity (body mass index >39 kg/m²); history of prematurity; asthma or second-hand smoke exposure; patients with upper respiratory infection symptoms such as nasal drainage, cough, or fever within 7 days of the date of surgery; American Society of Anesthesiologists (ASA) physical status ≥ 3; and emergency case status. A recruitment goal was set at 10 patients for each of 3 weight ranges (5.0-9.9 kg; 10-14.9 kg; and 15-20 kg) for each group. The team responsible for the care of the patient was consulted to ensure the patient met none of the aforementioned exclusion criteria, and that the chosen airway management strategy was consistent with deficits in the respective size groups to avoid over-
recruiting for a given group. Neither the patient care team nor the research team were blinded to the study group.

**Intraoperative Management**

Patients were taken to the operating room, where standard monitors were applied, including pulse oximetry, electrocardiogram, blood pressure, temperature, capnography, and end-tidal gas analysis. Induction of anesthesia was carried out with sevoflurane in oxygen or oxygen/nitrous oxide. Intravenous access was obtained. Each patient was administered a standardized relaxant dose of 0.7 mg/kg rocuronium. Airway management and selection of airway device were at the discretion of the patient’s clinical care team and had been determined prior to consent for participation.

In the case of patients who received an ETT, the airway was secured and the patient was subsequently placed on the anesthesia ventilator (Avance CS2®, GE Healthcare, Chicago, IL) using pressure control ventilation to deliver a tidal volume of 10 mL/kg at a rate of 20 breaths per minute. Positive end-expiratory pressure (PEEP) was set to 5 cmH₂O. The ventilator rate was adjusted as necessary to maintain end-tidal carbon dioxide (ETCO₂) in the range of 38 to 45 mmHg, and the inspiratory pressure was adjusted to maintain tidal volume of 10 mL/kg. Cuffed ETT size was determined using the Duracher formula (ETT internal diameter = Age in years/4+3.5) [8]. Absence of leak around the ETT was confirmed with auscultation. Endotracheal tube cuff pressure was not measured.

For the SGA device arm of the study, an air-Q® Masked Laryngeal Airway device was used (Cookgas, St. Louis, MO), and a similar procedure was followed. Initial device size was determined
according to the manufacturer’s recommendations based on weight. Following placement of the air-Q®
the presence of an adequate airway seal, defined as a sealing pressure >16 cm H₂O, was checked by
manually increasing the airway pressure and noting the pressure at which a leak was audible. The
patient was then placed on the anesthesia ventilator in pressure control mode with initial settings of
inspiratory pressure of 17 cm H₂O with PEEP of 5 cm H₂O and a rate of 20 breaths per minute. As in
the ETT group, the inspiratory pressure was then adjusted to maintain a tidal volume of 10 mL/kg, and
the respiratory rate (RR) was adjusted to maintain ETCO₂ in the range of 38 to 45 mmHg. Additionally,
the leak fraction (defined as the ratio of exhaled tidal volume to inspired tidal volume) was observed. A
ratio of <0.9 was considered to be excessive and the patient was either excluded or had the air-Q®
exchanged for the next size up and these parameters were reassessed. The rate was then adjusted as
necessary to maintain ETCO₂ in a similar range to the ETT group.

Following ETT or air-Q® placement a disposable optical detector attached to the Respironics
NM3® monitor (Philips North America, Andover, MA, USA) was then inserted into the anesthesia
circuit for all patients, in between the airway device and the circuit Y-piece. The time at which the
detector was inserted was considered time zero. After 2 minutes, the exhaled tidal volume (Vₑ),
inspiratory pressure, PEEP, RR, and oxygen saturation (SpO₂) were recorded from the standard
anesthesia monitor, and the airway deadspace (Vₑₐₑ, the sum of anatomic and device deadspace),
ETCO₂, volume of carbon dioxide (VCO₂), airway resistance (Rₑₐₑ), and dynamic compliance (Cₑₐₑ) were recorded from the NM3 monitor. This was repeated at 2-min intervals for 10 minutes. All
measurements were recorded at each time point.

Following the fifth measurement in each patient, the disposable optical detector was removed
from the anesthesia circuit and care was deferred to the clinical team caring for the patient. At this time
the patient’s participation in the study was considered to be complete. Any adverse events associated with ongoing management of the case as well as any events at the time of emergence were recorded.

**Statistical analysis**

Initial pilot data in 10 patients (5 ETT and 5 air-Q®) revealed that the airway and apparatus deadspace associated with an ETT was 3.2 mL/kg compared to a volume of 5.1 mL/kg associated with the air-Q® with a standard deviation of 1.9 mL. Using this information, sample size calculations were created; this revealed that with a power of 90% and an alpha of 0.05, a minimal sample size of 20 patients per group would provide the ability to detect at least a difference of 2 mL/kg in the primary outcome of airway deadspace/kg between groups. Further, *a priori*, we decided to recruit 10 patients for each of 3 weight ranges (5.0-9.9 kg; 10.0-14.9 kg, and 15.0-20.0 kg) to obtain a more evenly distributed sample across a range of weights for both the ETT tube and the air-Q® group. Thus, the study aimed for 60 total subjects (30 ETT and 30 air-Q®). This would also allow for a possible attrition and still maintain an adequate sample size.

Outcome measurements were recorded every 2 minutes for 10 minutes total, and the 5 data points were averaged for analysis. Descriptive statistics, including medians and interquartile ranges for demographic data not normally distributed and means/95% confidence intervals for continuous measures and frequencies and proportions for categorical data, were calculated. Mann-Whitney test for non-parametric data, independent t-tests for normally-distributed continuous measures and Fisher’s Exact Tests for categorical variables were used to test for differences between the two device groups. Spearman correlation coefficients were used to assess the strength of association between continuous variables. Analysis of variance (ANOVA) regression models were created to analyze the relationship
between outcome measures and independent predictors. P-values $<$0.05 were assumed to be significant.

SAS (version 9.4, Cary, NC, USA) was used for all analyses.
Results

A total of 70 patients were approached for the study (figure 1). Sixty-two patients were consented for participation. Two patients were excluded after consent and did not participate in the study: one patient's weight range had already been filled, and another patient was excluded because the surgeon requested the team caring for the patient not use muscle relaxant for the case. A total of 60 patients were enrolled, 30 in each group. One patient from the air-Q® group was excluded from analysis due to incomplete data as a result of monitor malfunction. All patients had leak fractions greater than 0.9 except one who had a SGA initially; the device was exchanged for an ETT and this patient was secondarily assigned to the ETT group. Demographics for both device groups are summarized in Table 1. There were no significant differences between groups. No significantly morbid events were noted in any patient during the entire surgical or anesthetic epoch up to and including discharge from the post anesthesia care unit.

There was no statistically significant difference between air-Q® and ETT groups in exhaled tidal volume, ETCO₂, or total minute ventilation although minute ventilation in the air-Q® group did trend higher. These results are summarized in Table 2. There was a significant difference in weight-adjusted deadspace volume (the sum of airway deadspace and device deadspace) between the air-Q® and ETT groups of 1.1 [95%CI 0.7 - 1.5] mL/kg, p<0.001. Weight-adjusted deadspace volume (in mL/kg) increased significantly with decreasing weight for both the air-Q® and ETT groups (Figure 1).

Weight-adjusted deadspace volume varied more significantly from one size of ETT to another (p<0.001) but did not vary with weight for each specific size. Conversely, for the air-Q® group, weight-adjusted deadspace volume did not vary significantly between sizes (p=0.07), but retained an inverse relationship with weight for each specific size. This is summarized in Figure 2.
Discussion

The primary finding of this study is that use of an air-Q® SGA is associated with significantly more apparatus and anatomic deadspace when compared to an ETT. Further, while this difference is intuitive, the actual magnitude of weight-adjusted deadspace, especially in very young children, exceeds reasonable expectations of tidal volume during spontaneous ventilation in young children undergoing anesthesia [3]. Additionally, this deadspace will have to be compensated for when selecting mechanical ventilator settings to maintain CO₂ homeostasis calling into question the wisdom of smaller tidal volume, lung protective ventilation strategies in very young children even in some cases when an ETT is present. While some might argue that the although the result is statistically significant, the overall difference in deadspace/kg between the devices is be less clinically significant. In assessing this though it is important to note that the difference enclosed by the 95% confidence interval may actually be significantly higher, especially in very young children. These findings are clinically important because they may inform airway device selection for a given patient, as well as guide the clinician’s approach to determining the length of time they allow a patient to breathe spontaneously through a SGA.

Overall, there were no adverse events in our study group, and mild hypercarbia is generally well tolerated in healthy children, but for select patients increased airway deadspace may be clinically relevant. For example, children with pulmonary hypertension or certain types of congenital heart disease may deteriorate with hypercapnia and respiratory acidosis [9]. In these more fragile populations, the clinician may want to use an ETT instead of a SGA and/or the clinician may simply need to compensate with more aggressive mechanical ventilation or reduce periods of spontaneous ventilation [3].
Another interesting finding was that the weight-adjusted deadspace, increases with decreasing patient size for both devices—not just the air-Q®. The inverse variation of weight-adjusted deadspace with both devices highlights the fact that, just because smaller devices are available for pediatric patients, non-linear scaling in physiologic processes and anatomy in smaller patients may require additional compensation strategies that may not at first glance be apparent. This is consistent with prior work in which the in vitro device volumes of several SGA devices were measured, including those for the air-Q® [10]. When the air-Q® device volume is normalized to the manufacturer’s recommended weight ranges, per kilogram device volume increases with decreasing device size: 0.66-1.17 mL/kg for air-Q® 2.0, 0.84-2.0 mL/kg for air-Q® 1.5, 1.4-2.5 mL/kg for air-Q® 1.0, and up to 3.3 mL/kg for air-Q® 0.5.

Another interesting finding of our study is that there appears to be a significant difference in the in vivo weight-adjusted deadspace from one size ETT to another, but not from one size air-Q® to another. This is likely related to a combination of two factors. First, there is a greater increase in apparatus volume as air-Q® size increases (up to 51%) as compared to ETTs (up to 25%) for the sizes used in the study. Second, a greater fraction of anatomic deadspace is inherent when using a SGA as compared to an ETT, which excludes anatomic deadspace above the cuff. Practically speaking then, up- or down-sizing an ETT may make a significant difference in deadspace for a specific patient, but less so for a SGA which sometimes are upsized because of an inadequate sealing pressure.

Finally, it is important to note that despite significantly larger total deadspace in the air-Q® group, there was no statistically significant difference in ETCO₂, V̇ eo, and minute ventilation between groups as one would expect. While the study was not necessarily powered to detect a difference in these parameters, one would expect to see a difference in ETCO₂ if the minute ventilation is the same with a larger proportion of the minute ventilation being from deadspace ventilation. As additional
apparatus deadspace is introduced into the circuit, a smaller percentage of the delivered tidal volume ventilates the alveoli, and exhaled CO₂-saturated gas is diluted by inhaled volume that did not exchange gas. In these cases, an increase in deadspace may actually lead to an increase in the A-a gradient. Over time, increasing PₐCO₂ will lead to an increase in ETCO₂ despite the increased deadspace. However, ETCO₂, due to the increased A-a gradient, may remain an underestimate of PₐCO₂, in proportion to the deadspace. It is likely that in our study, a measurement of PₐCO₂ in all children would have shown that the higher deadspace air-Q® group had higher PₐCO₂ values, and thus they were relatively hypoventilated, compared to the ETT group, despite similar ETCO₂ between groups. This also raises the possibility that during patient care a similar situation arises, whereby the clinician using a large deadspace airway device derives a false sense of security from a “normal” ETCO₂, when the patient is actually hypoventilated and hypercarbic. This may be of particular importance in smaller children in which the ratio of deadspace to tidal volumes is larger and therefore the gradient may be larger leading to a greater relative underestimate of ventilation adequacy using minute ventilation and ETCO₂.

The results of this study are consistent with the work of Chhibber, et al. who compared the ETCO₂ and arteriolar carbon dioxide (PₐCO₂) levels in infants and children undergoing ventilation with an LMA Classic® or ETT using a crossover design [11,12]. In both studies, the authors found that patients had higher ETCO₂ and PₐCO₂ values, as well as an increased ETCO₂-PₐCO₂ difference with the LMA versus an ETT using similar ventilator settings. The disproportionate effects of apparatus deadspace on smaller children have also been alluded to in prior studies by Kwon and Chau who measured increased levels of ETCO₂ when adding heat and moisture exchanger to the ventilation circuit under similar ventilator settings [13,14]. Finally, in a mathematical modeling study, Pearsall, et al. derived equations to evaluate PₐCO₂ and RR as a function of weight and deadspace [15]. They found that the relationship between both PₐCO₂ as well as minute ventilation as a function of apparatus
deadspace is exponential, and stressed the importance of patient weight since $V_d/V_t$ increases more rapidly for smaller patients as deadspace increases.

**Limitations**

This study has several limitations. First, the sample size is small and the study was not powered to evaluate differences in secondary outcomes including minute ventilation, so while there was a trend toward increased minute ventilation to maintain similar ETCO$_2$ in the air-Q® group, it was not found to be statistically significant. Second, these results apply strictly to the air-Q® SGA, and while we suspect other SGAs will add varying amounts of deadspace based on their different designs, we did not specifically evaluate other devices and further study is warranted in that regard [10]. Additionally, group selection was determined prior to enrollment in the study according to the preference of the attending anesthesiologist assigned to a given case, not randomized. This may be a source of selection bias, although both groups had similar baseline demographics with similar underlying patient characteristics.

**Conclusion**

In healthy children undergoing positive pressure ventilation for elective surgery, the air-Q® supraglottic airway introduces significantly greater airway dead space than an endotracheal tube. Additionally, airway dead space, and minute ventilation required to maintain normocarbia, appear to increase with decreasing patient weight irrespective of whether a supraglottic airway or endotracheal tube is used.
References


<table>
<thead>
<tr>
<th></th>
<th>air-Q® (n=29)</th>
<th>ETT (n=30)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (mo)</td>
<td>31 (12-50)</td>
<td>18 (8-43)</td>
<td>0.23</td>
</tr>
<tr>
<td>Weight Class (kg)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5.0-9.9 kg</td>
<td>12.7 (9.3-16.4)</td>
<td>11.4 (8.9-16.6)</td>
<td>0.79</td>
</tr>
<tr>
<td>10.0-14.9 kg</td>
<td>9 (31.0%)</td>
<td>10 (34.5%)</td>
<td></td>
</tr>
<tr>
<td>15.0-20.0 kg</td>
<td>10 (34.5%)</td>
<td>10 (34.5%)</td>
<td></td>
</tr>
<tr>
<td>Male gender</td>
<td>28 (96.6%)</td>
<td>29 (96.7%)</td>
<td>0.99</td>
</tr>
<tr>
<td>ASA Status 1</td>
<td>25 (86.2%)</td>
<td>21 (70.0%)</td>
<td>0.21</td>
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</tbody>
</table>

Reported as median (IQR) or number (%). ASA = American Society of Anesthesiologists
Table 2. Main Outcome Results Using Volumetric Capnography for Patients with an air-Q® SGA Versus an Endotracheal Tube Following Induction of General Anesthesia and a Standardized Ventilation Protocol.

<table>
<thead>
<tr>
<th></th>
<th>air-Q® (n=29)</th>
<th>ETT (n=30)</th>
<th>P-value</th>
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<tr>
<td>ETCO₂ (mmHg)</td>
<td>41.6 (5.0)</td>
<td>41.2 (4.6)</td>
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<td>VCO₂ (mL/min)</td>
<td>64.6 (18.1)</td>
<td>63.4 (22.9)</td>
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<tr>
<td>Vₜₑ (mL)</td>
<td>116.8 (35.4)</td>
<td>117.5 (40.6)</td>
<td>0.95</td>
</tr>
<tr>
<td>Vₜₑ by weight (mL/kg)</td>
<td>9.3 (1.0)</td>
<td>9.5 (1.7)</td>
<td>0.61</td>
</tr>
<tr>
<td>Mean deadspace difference (mL)</td>
<td>15.0 [11.5 - 18.5]</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mean deadspace by weight difference (mL/kg)</td>
<td>1.1 [0.7 - 1.5]</td>
<td>&lt;0.001</td>
<td></td>
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<tr>
<td>Minute ventilation by weight difference (mL/kg-min)</td>
<td>8.5 [-11.6 - 28.4]</td>
<td>0.40</td>
<td></td>
</tr>
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</table>

Values are presented as mean (SD) or mean difference [95% confidence interval]. ETT = endotracheal tube; ETCO₂ = end-tidal CO₂; VCO₂ = volume of carbon dioxide; Vₜₑ = exhaled tidal volume.
Figure 1. CONSORT Diagram.
Figure 2. Weight-adjusted deadspace volume (WADSV) for each device versus patient weight. Best-fit model ($R^2=0.930$) is $WADSV = 0.0164w^2 - 0.597w + 1.172d + 7.604$ where: $w$ is the child's weight; $d$ is the airway device: equals 0 for ETT, 1 for air-Q®.
**Figure 3.** Boxplot of weight-adjusted deadspace volume (WADSV) for endotracheal tube (ETT) and air-Q® as a function of device size. Box upper and lower borders denote 75th and 25th percentile values, respectively, and enclosed line denotes median value. Whiskers denote range. Note significant difference in WADSV when comparing sizes for ETT. WADSV for air-Q® follows a similar trend but is not statistically significant.