Prediction of Pediatric Endotracheal Tube Size by Ultrasonography

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ABSTRACT

Background: Formulas based on age and height often fail to reliably predict the proper endotracheal tube (ETT) size in pediatric patients. We, thus, tested the hypothesis that subglottic diameter, as determined by ultrasonography, better predicts optimal ETT size than existing methods.

Methods: A total of 192 patients, aged 1 month to 6 yr, who were scheduled for surgery and undergoing general anesthesia were enrolled and divided into development and validation phases. In the development group, the optimal ETT size was selected according to standard age- and height-based formulas for cuffed and uncuffed tubes. Tubes were replaced as necessary until a good clinical fit was obtained. Via ultrasonography, the subglottic upper airway diameter was determined before tracheal intubation. We constructed a regression equation between the subglottic upper airway diameter and the outer diameter of the ETT finally selected. In the validation group, ETT size was selected after ultrasonography using this regression equation. The primary outcome was the fraction of initial cuffed and uncuffed tube sizes, as selected through the regression formula, that proved clinically optimal.

Results: Subglottic upper airway diameter was highly correlated with outer ETT diameter deemed optimal on clinical grounds. The rate of agreement between the predicted ETT size based on ultrasonic measurement and the final ETT size selected clinically was 98% for cuffed ETTs and 96% for uncuffed ETTs.

Conclusions: Measuring subglottic airway diameter with ultrasonography facilitates the selection of appropriately sized ETTs in pediatric patients. This selection method better predicted optimal outer ETT diameter than standard age- and height-based formulas.

What We Already Know about This Topic

- The proper endotracheal tube size for children is poorly predicted by formulas relying on age and height.

What This Article Tells Us That Is New

- In 192 children aged 1 month to 6 yr, ultrasound measurement of subglottic airway diameter better predicted appropriately sized endotracheal tube than traditional formulas using age and height.

INTUBATION of pediatric patients with an endotracheal tube (ETT) that is too small may result in insufficient ventilation, poor reliability of end-tidal gas monitoring, leakage of anesthetic gases into the operating room environment, and an enhanced risk of aspiration. In contrast, an ETT that is too large can cause upper airway damage (e.g., local ischemia, ulceration, scar formation) and the potential for subsequent subglottic stenosis.

Age-based formulas, such as those of Cole and Motoyama, have been used to estimate optimal ETT size for more than half a century. Predictive formulas for appropriate ETT size have also been based on patient weight and height. However, none of these systems work especially well. The result is that repeated laryngoscopies are often necessary to identify the appropriate tube for individual patients.

Recent reports suggest that the diameter of the subglottic upper airway can be determined by ultrasonography in healthy young adults and pediatric patients. However, the extent to which ultrasonography can predict optimal ETT size in pediatric patients remains to be determined. Therefore, we tested the hypothesis that subglottic diameter,
as determined by ultrasonography, better predicts optimal ETT size than existing methods.

Materials and Methods

This study was approved by the Review Board for Human Experiments at Kyoto Prefectural University of Medicine (Kyoto, Japan). Written informed consent was obtained from custodial adults. We enrolled a total of 192 patients aged 1 mo to 6 yr, split into development and validation phases. Each patient was scheduled for surgery requiring general endotracheal anesthesia. Those with conditions known or suspected to predispose them to laryngeal or tracheal pathology were excluded. General anesthesia was induced by inhalation of sevoflurane or intravenous administration of thiopental. Vecuronium was given to all patients for muscle relaxation.

Fig. 1. Photograph and illustration of ultrasonography of the neck to measure subglottic diameter. Patient consent was obtained for use of this photograph.

Our primary endpoint was a regression of outer ETT diameter against subglottic diameter as determined by ultrasonography. In a pilot study, the SD of subglottic diameter was 2.9 mm, the correlation coefficient between ETT outer diameter (OD) and subglottic diameter was 0.7. The slope estimate obtained from regression equation was 0.5. Assuming a true regression slope of 0.5, a total of 19 subjects were required to reject the null hypothesis that this slope equals zero with 90% power at an α level of 0.01.13 Our primary goal, though, was to determine the extent to which variability in optimal ETT size can be explained by the variability in the tracheal dimension as assessed by ultrasonography. We therefore increased the number of subjects to 48 each for the cuffed and uncuffed ETT groups (n = 96).

Development Phase

In the development phase, we evaluated 48 patients who were intubated with a cuffed ETT and an additional 48 who were intubated with an uncuffed ETT. Selection of cuffed versus uncuffed ETT was determined solely by the preference of the anesthesiologists. Within each study group, an equal number of patients were recruited from three weight subgroups: 3 to less than 9 kg, 9 to less than 15 kg, and 15 to less than 21 kg.

Subglottic diameter was estimated with B-mode ultrasonography (SonoSite 180, SonoSite, Inc., Tokyo, Japan) with a 5–10-MHz linear probe positioned on the midline of the anterior neck (fig. 1). To avoid any confusion between the cricoid cartilage and a tracheal ring, ultrasonography began with local-i

ization of the true vocal folds as paired hyperechoic linear structures that moved with respiration and swallowing before patients were paralyzed. The probe was then moved caudally to visualize the cricoid arch (i.e., round hyperechoic structure with hyperechoic edges). The transverse air-column diameter was measured at the lower edge of the cricoid cartilage after patients were paralyzed, and was considered tracheal diameter. These measurements were performed without ventilation or positive end-expiratory pressure to minimize fluctuation in tracheal diameter.

The ultrasonographer had considerable experience performing laryngeal ultrasonography before the starting this investigation. Typically, the ultrasound measurements took approximately 30 s.

The trachea was then intubated using direct laryngoscopy. Size of the initial tube was selected as follows: (1) uncuffed tubes, with the Cole formulas: ID (inner diameter) in mm = 0.25 × (age in years) + 4; (2) cuffed ETTs in children aged 2 yr or older, with the Motoyama formulas: ID in mm = 0.25 × (age in years) + 3.5; (3) cuffed ETTs in children younger than 2 yr, with the Khine formulas: ID in mm = 0.25 × (age in years) + 3.0.

If there was resistance to ETT passage into the trachea, or there was no audible leak when the lungs were inflated to a pressure of 20–30 cm H2O, the tube was exchanged with one that was 0.5 mm smaller. In contrast, the ETT was exchanged for one that was 0.5 mm larger if a leak occurred at an inflation pressure less than 10 cm H2O.12,14 Tube size was considered optimal when a tracheal leak was detected at an inflation pressure between 10–20 cm H2O with either uncuffed tubes or deflated cuffed tubes. Cuff leak evaluation was performed by the same two well-trained investigators. Interrater variability of the cuff leak pressure values between the two observers was less than 10% (intraclass coefficient of the selected cuff leak pressure = 0.88).

After intubation with an appropriately sized tube, tracheal diameter was measured again, as was ETT OD (i.e., round hyperechoic structure, fig. 2). Ultrasonic estimates of tracheal diameter and airway leak pressure measurement were performed by different investigators, each of whom was blinded to the other’s data. Ultrasonography and airway leak pressure measurement were performed in the supine position, with the head in a neutral position with slight extension.15

Linear regression was used to determine the relationship between subglottic diameter and the OD of optimally sized...
ETT. For comparison, regression analysis was similarly used to determine the relationship between the OD of optimally sized ETTs and patient age and height.

Validation Phase
In the validation phase, we evaluated an additional 48 pediatric patients intubated with cuffed ETTs and an additional 48 intubated with uncuffed ETTs. Patients were again evenly selected from the same three weight subgroups (n = 96). Initial ETT size in validation patients was based on the regression formula constructed in the development phase. The tube size closest to that predicted by the regression was used. Again, tubes were replaced as described above until an optimal size was identified.

The primary outcome was the fraction of initial cuffed and uncuffed tube sizes, selected by the regression formula, that proved clinically optimal. The fraction of tubes that were initially optimal in the validation phase was compared with those that were deemed optimal in the development phase using chi-square test. The fraction of tubes that were initially optimal in the validation phase was similarly compared with tube size as predicted using the regression formulas based on age and height.

Statistical Analyses
Data were analyzed using InStat software (version 3.06.32; GraphPad Software, Inc., La Jolla, CA). Simple and multiple regression equations for the relationships were calculated using the method of least squares fitting (fig. 3). The Bland-Altman method was used to compare the ETT OD and subglottic diameter. Data are reported as mean ± SD unless otherwise indicated; P < 0.05 was considered statistically significant.

Results
Morphometric and demographic characteristics of the patients were similar at both phases and for both types of ETT (table 1). In the development phase, agreement between the clinically optimal versus predicted ETT size—as based on the Cole formula for uncuffed and the Motoyama and Khine formulas for cuffed—was only 35% for cuffed and 60% for uncuffed.

Subglottic upper airway diameter was highly correlated with the OD of the ETT finally selected with a regression
Table 1. Pediatric Patient Demographics by Weight-assigned Subgroup (N = 192)

<table>
<thead>
<tr>
<th>Weight Group</th>
<th>Development Phase (n = 32)</th>
<th>Validation Phase (n = 32)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cuffed</td>
<td>Uncuffed</td>
<td>Cuffed</td>
</tr>
<tr>
<td>3–9 kg Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height, cm</td>
<td>66 ± 10</td>
<td>69 ± 7</td>
<td>66 ± 11</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>6.5 ± 1.7</td>
<td>7.6 ± 1.1</td>
<td>6.7 ± 2.1</td>
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<tr>
<td>Age, mo</td>
<td>9 ± 7</td>
<td>13 ± 10</td>
<td>9 ± 6</td>
</tr>
<tr>
<td>9–15 kg Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height, cm</td>
<td>83 ± 8</td>
<td>86 ± 7</td>
<td>10.8 ± 1.4</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>10.6 ± 1.4</td>
<td>11.5 ± 1.6</td>
<td>24 ± 15</td>
</tr>
</tbody>
</table>

All data are mean ± SD unless otherwise specified.

equation of the ETT OD of 0.46 × (subglottic diameter) + 1.56, $R^2 = 0.90$ for cuffed, and 0.55 × (subglottic diameter) + 1.16, $R^2 = 0.90$ for uncuffed (fig. 3). Bland-Altman analysis of the OD and subglottic diameter of optimally sized ETTs noted a bias of 3.8 mm with the limits of agreement (bias ± 1.96 SD) of 2 and 5.7 mm in cuffed, and a bias of 3.3 mm with the limits of agreement of 1.9 and 4.6 mm in uncuffed.

Age in months also correlated with optimal ETT size in mm, although the correlation was weaker than for subglottic diameter with the ETT OD of 0.027 × (age) + 5.2, $R^2 = 0.76$ for cuffed, and 0.030 × (age) + 5.4, $R^2 = 0.76$ for uncuffed. Height in cm also correlated with optimal ETT size in mm, although the correlation was again weaker than for subglottic diameter with an OD of 0.037 × (height) + 2.9, $R^2 = 0.79$ for cuffed and an OD of 0.044 × (height) + 2.6, $R^2 = 0.82$ for uncuffed.

In the validation phase, the rate of agreement between the clinically optimal and the predicted ETT size based on ultrasonographic measurement was 98% for cuffed and 96% for uncuffed ($P < 0.001$ compared with the formulas of Cole, Motoyama, and Khine). The rate of agreement between the clinically optimal and the predicted ETT size based on ultrasonographic measurement was also significantly better than predictions from the regression equations based on age (35% cuffed vs. 60% uncuffed, $P < 0.001$, fig. 4) and height (46% cuffed vs. 60% uncuffed, $P < 0.001$).

Discussion

Age-based formulas such as those of Cole and Motoyama remain in common use. However, the agreement rate of age-based pediatric ETT size selection using the Cole formula was as low as 47–77% in previous studies, $P < 0.001$, a finding similar to that of the present investigation (35% cuffed vs. 60% uncuffed). We note, though, that these calculations assume that the clinically selected ETT was the only size that fit the criteria—an assumption that is surely not always the case. Nonetheless, the disparity between age- and height-based formulas and the clinically optimal ETT size was substantial—whereas ultrasound was highly predictive. Furthermore, age-based formulas generally predicted larger sizes than proved clinically optimal, sometimes by two or even three sizes. To compensate for individual variation in growth, others have suggested that pediatric ETT size be selected in 90% of patients by a patient length-based technique (e.g., Broselow tape). However, such methods have limitations because these formulas cannot reflect variation in the growth of internal organs.

The present study showed that direct measurement of subglottic diameter by ultrasonography has significant advantages in predicting optimal pediatric ETT size. A previous pilot study reported the usefulness of measuring the subglottic diameter by ultrasonography in 10 pediatric patients. The present prospective clinical study extended the findings of that study by showing a higher correlation between ETT OD and subglottic diameter than between OD and patient age or height. Furthermore, there was a high rate of agreement between predicted and clinically selected ETT size in the validation phase by using the regression equation constructed from 96 pediatric patients in the development phase. We used the OD for our regressions because it can vary by as much as 1 mm at any given ID depending on the manufacturer.

A report on the feasibility of ultrasound to assess subglottic diameter showed a strong correlation between ultrasonography and magnetic resonance image measurements of the
transverse subglottic diameter, suggesting that ultrasonographic measurement could adequately assess the subglottic diameter.\textsuperscript{11}

The subglottis, as bound by the complete cartilaginous ring of the cricoid cartilage, was long believed to be the narrowest part of the pediatric larynx. A recent report, however, identified the narrowest portion to be at the vocal cord and subvocal cord level in paralyzed children.\textsuperscript{13} However, measuring the tracheal diameter consistently at these levels in all patients was difficult because of the blurred ultrasonic visualization of the vocal cord. Therefore, we measured subglottic diameter at the lower edge of the hypoechoic cricoid cartilage. This measure represented a reliable and consistent value that could be compared among patients.

Increasing discrepancy between uncuffed ETT OD and subglottic diameter in proportion as a function of subglottic cartilage during the third decade of life, ultrasonography can be applied with few problems in pediatrics.\textsuperscript{20}

Optimal ETT size could be selected from measurement of the tracheal diameter on chest radiography.\textsuperscript{21} A good correlation in tracheal diameter between computed tomography and chest radiography indicates that the latter could give a representative measurement of tracheal diameter.\textsuperscript{22} A length of approximately 70% (uncuffed) or 60% (cuffed) of the tracheal diameter on chest radiography is reported to be a possible indicator of ETT ID. However tracheal diameter on chest radiography does not necessarily reflect the subglottic diameter, the narrowest part of the pediatric larynx.

In clinical anesthesia practice, we usually select pediatric ETT sizes based on ID. However, the relationship between ID and OD differs among manufacturers, complicating age-based pediatric ETT size selection. Further, although there are no differences in the OD between cuffed and uncuffed ETTs used in the present study (table 2), selected ODs have a tendency to be smaller in cuffed than uncuffed ETTs (fig. 3).

Cuffed ETTs can safely be used in pediatric populations, resulting in fewer adverse effects than uncuffed ETTs. A recent study found that there were no significant differences in the use of racemic epinephrine for postextubation subglottic edema, the rate of successful extubation, or the need for tracheotomy between intubations with cuffed versus uncuffed ETTs.\textsuperscript{16–18}

In summary, previous established formulas based on age poorly predicted pediatric ETT size. In contrast, subglottic upper airway diameter measured by ultrasonography was a good predictor of correct cuffed and uncuffed ETT sizes for pediatric patients.

### Table 1. Continued

<table>
<thead>
<tr>
<th>Inner Diameter, mm</th>
<th>Outer Diameter, mm</th>
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<tbody>
<tr>
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