Evaluation of a New Thin-Walled Endotracheal Tube for Use in Children*

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Conventional endotracheal tubes have high intrinsic resistive properties due to their high outer-to-inner diameter ratio. This has significant disadvantages in the treatment of the small neonatal or pediatric patient as work of breathing increases with decreasing internal radius. Diagnostic and therapeutic procedures, including suctioning, may be very difficult in patients with small endotracheal tubes. We therefore measured airway resistance and pressure differential during simulated mechanical ventilation using proximal and distal endotracheal tube flow transducers. Conventional and new, ultrathin-walled endotracheal tubes reinforced with flat stainless steel or a novel, crush-proof nickel-titanium alloy were compared using fixed ventilator settings. Ventilation through the ultrathin-walled tubes resulted in a significantly reduced airway resistance (p<0.01). These new ultrathin-walled endotracheal tubes showed flow characteristics typical of much larger conventional endotracheal tubes: the 3.2-mm internal diameter had an airway resistance (Raw) of 36, while a standard 2.5-mm internal diameter endotracheal tube had a Raw of 146. Both endotracheal tubes have identical external diameters of 3.6 mm. We conclude that ultrathin-walled endotracheal tubes could have a significant role in the treatment of the ventilated child by facilitating interactive ventilation and maintenance of airway patency and may make procedures such as fiberoptic endoscopy and intrapulmonary ventilation using reverse-thrust catheters possible in the small child.

(CHEST 1996; 109:1335-38)

Key words: airway resistance; airway stenosis; endotracheal tubes; mechanical ventilation; work of breathing

Abbreviations: CPAP = continuous positive airway pressure; ETT = endotracheal tube; ID = internal diameter; PSV = pressure support ventilation; UTTS = ultrathin-walled two-stage

The standard endotracheal tubes (ETTs) currently employed for mechanical ventilation of neonatal and small pediatric patients are disadvantageous due to the unfavorable intrinsic resistive properties caused by the relatively thick walls resulting from current manufacturing processes. Flow within ETTs is almost never laminar, but turbulent, further elevating airflow resistance beyond that of laminar airflow, where a decrease in diameter causes an increase in airway resistance inversely proportional to the fourth power of the internal radius.

Ventilatory management of the infant and small child may be complicated by many factors. Studies performed by Shapiro et al4 and Fiastro et al5 demonstrate marked increases in work of breathing with each 1-mm decrease in ETT caliber. Infants ventilated through small ETTs have prolonged inspiratory and expiratory time constants (the product of compliance and resistance) leading to inefficient inspiration with smaller delivered tidal volumes for a given pressure and inadvertent positive end-expiratory pressure due to a prolonged expiratory time during full ventilatory support.6

Increased airway resistance may play a role in the dysynchrony between patient effort and ventilator response frequently noted in infants when attempts are made to provide interactive ventilatory support with modes such as pressure support ventilation (PSV) or neonatal patient-triggered ventilation. Patients displaying severe dysynchrony (“fighting the ventilator”) are frequently treated with additional sedation or even neuromuscular blockade in an effort to improve phase synchrony. These interventions are not without risk and may contribute to a prolonged ventilator course.7-9

The high airway resistance of small ETTs may make spontaneous ventilation with continuous positive airway pressure (CPAP) impossible, mandating mechanical ventilation in certain patients in whom it could be avoided. Patient-related factors such as ventilatory muscle weakness and fatigue due to dynamic hyperinflation may be worsened by the high intrinsic resistive load of small ETTs.
Small ETTs limit access to the lower airway for procedures such as bronchoscopy and BAL and may be very difficult to suction and clear, particularly in the presence of significant large airway inflammation due to tracheitis or laryngotracheobronchitis.  

High intrinsic resistance and small internal diameters (IDs) become increasingly important when small tubes are placed in the neonate, small infant, or child in the presence of airway abnormalities, stenotic lesions, or airway edema. An ultrathin-walled, low-resistance ETT was designed to circumvent these problems. We tested this new ETT in vitro during simulated mechanical ventilation to quantitate the difference generated in airway resistance when comparing these new tubes with conventional ETTs of comparable external diameter.

**Materials and Methods**

Mechanical ventilation was simulated using a pediatric ventilator (VIP Bird Infant/Pediatric Ventilator; Bird Products, Palm Springs, Calif), BiCure Varflex transducers (CP-100 Neonatal Monitor; Bicore Monitoring Systems; Irvine, Calif) were placed on the proximal and distal ends of 2.5- to 5.0-mm ID standard ETTs as well as 2.2-, 3.2-, and 4.6-mm ID ultrathin-walled two-stage (UTTS) ETTs. The transducer on the distal end was connected to a simulator (Ohmeda Lung Simulator, Harlow, Essex, United Kingdom). All tubes were supported in the straight position during simulated ventilation.

Ventilator settings were fixed at a tidal volume of 100 mL, a frequency of ten breaths per minute, and no positive end-expiratory pressure. Room air was used. The flow rate was set at 10 L/min. Mean airway resistance and pressure gradients were measured during six individual studies and averaged. The experiment was then repeated using a flow rate of 20 L/min. Commercially available ETT Critical Care, (Mallinckrodt ETTs) were compared with specially manufactured experimental ETTs. In brief, these prototype ETTs were created in the laboratory using a previously described method. Either stainless steel flat wire or a crushproof nickel-titanium shape memory alloy (Nitinol) was used. This was coiled as a flat wire over a medical grade polyurethane (Surethane; Cardiac Control Systems; Palm Coast, Fla) coated mandrel. This material is a medical grade polyurethane used in manufacturing cardiac assist devices. The coated mandrel was then overcoated with the same polyurethane solution. It was then cured, finished, and shaped in such a way that the final wall thickness was about 0.2 mm compared with the 0.6-mm wall thickness of a standard 2.5-ID ETT and the 0.85-mm thickness of the standard 4.5-mm ETT. These experimental tubes were left uncuffed and had a smooth distal tip when trimmed with scissors (Figs 1 and 2).

Two-stage ETTs were created using a mandrel that gradually tapered at a 2° angle in a manner superficially reminiscent of a Cole ETT but designed in such a way that the larger diameter section would reside within the oropharynx and a 1.2- to 1.8-cm-long, slightly narrower distal segment would remain within the tra-

![Figure 1. Cross sections of the ultrathin ETT (left) and a conventional ETT. Outer diameters are the same.](image1)

![Figure 2. The ultrathin ETT. The tube has been flexed to demonstrate lack of kinking.](image2)

### Table 1—Descriptive Statistics of Standard and Thin-Walled Tubes

<table>
<thead>
<tr>
<th>Raw at Tested Gas Flows*</th>
<th>N</th>
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<th>Median</th>
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<td>207</td>
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<td>1.05</td>
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<td>1.16</td>
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<td>45.00</td>
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<td>46</td>
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*Raw=mean airway resistance at 10 and 12 L/min.
were patients. External walled tubes: ETTs were significant decrease typical of much larger standard ETTs. The ultrathin-walled ETT ID was defined as the ID of the distal, tracheal portion of the tube.

Descriptive statistics are depicted in Table 1. Standard and thin-walled tubes of equivalent external diameter were compared using a two sample t test. A p value of less than 0.01 was considered statistically significant. A computer program was used (Minitab 10 release for Windows; Minitab, Inc; State College, Pa).

RESULTS

Resistance to flow, pressure differential, and a comparison of internal and external diameters are shown in Table 2.

Ultrathin-walled ETTs displayed flow characteristics typical of much larger standard ETTs. There was a dramatic decrease in resistance with the ultrathin-walled tubes: the resistance through the 2.2-ID UTTS, which has an external diameter of only 2.7 mm and could theoretically be placed in extremely small airways, was significantly lower than the resistance measured through the standard 2.5-mm ID ETT, which has a 3.6-mm outer diameter. The 3.2-mm ID UTTS, which has same external diameter as the standard 2.5-mm ID standard ETT, has the flow characteristics displayed by the standard 4.0-mm ID ETT.

Resistance to airflow increased at the higher flow rate of 20 L/min as would be expected, but was still significantly lower when the ultrathin-walled ETTs were compared with standard ETTs of comparable external diameter.

DISCUSSION

Wire-reinforced (armored) ETTs have long been available for the intraoperative management of neurosurgical patients. These tubes are created using a dip-coating process that results in a wall thickness approximatly the same as found in standard vinyl ETTs. The ultrathin crush-proof alloy (Nitinol) recently incorporated into ETT design combines strength with flexibility while minimizing ETT wall thickness. This technology lends itself well to additional modifications such as the incorporation of a distal monitoring lumen and the addition of traditional or novel cuff modifications: ultrathin-walled ETTs with no-pressure filmy distal attachments analogous to gills may play a role in the management of severe respiratory failure when it is important to maintain a stable, high mean airway pressure with minimal gas leakage. These tubes may also permit diagnostic or therapeutic bronchoscopic procedures and may also allow the incorporation of reverse-thrust endotracheal flush catheters for intratracheal pulmonary ventilation in selected patients.

As previously noted, the ultrathin-walled ETTs showed a consistently lower airway resistance when compared with a standard ETT with a slightly larger ID. We attribute this counterintuitive phenomenon to the two-stage design, where there is a significant reduction in airway resistance in the larger proximal oropharyngeal end.

It is anticipated that these tubes will facilitate interactive ventilatory modes such as PSV and neonatal pressure-triggered ventilation and may have a similar effect when spontaneous modes such as CPAP are entertained, by decreasing the imposed work of breathing thereby allowing enhanced triggering of currently available pressure-sensitive transducers.

In summary, airflow resistance in ultrathin-walled ETTs is significantly lower than that found in conventional ETTs of similar outer diameter. This can have important implications in the management of acute respiratory failure requiring full ventilatory support and when partial, interactive, or spontaneous modes are employed in patients recovering from respiratory failure. The need for emergent reintubation for acute ETT obstruction, with all its attendant risks, should decrease. Other potential benefits include improved airway access for bronchoscopy and novel ventilatory modes in a strong, light, flexible, crush-proof, and versatile ETT with minimal torque transmission and optimal flow characteristics. This technology may lend itself well to minimally invasive ventilatory techniques such as CPAP or PSV using a shorter, ultrathin walled tube placed in the nasopharynx.

Additional refinements to facilitate placement and adjustment of these novel ETTs will require further in vivo animal studies as well as evaluation in pediatric patients. These ETTs will also have to be subjected to evaluation by the appropriate American Standards Institute committees.

ACKNOWLEDGMENTS: This study was carried out using specially produced prototype ETTs and the commercially available Mallinckrodt ETTs. No extramural funding was received by any of

<table>
<thead>
<tr>
<th>ETT Size</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
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<th>Raw2</th>
<th>ΔP1</th>
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<td>36</td>
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<td>24.7</td>
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</table>

OD=external diameter; Raw1 and Raw2=airway resistance at 10 and 20 L/min; ΔP=pressure differential (drop) measured at 10 L/min; ST=standard ETT.

*p<0.001 vs 2.5 standard ETT.

**p<0.001 vs 3.5 standard ETT.

Chea,11-13 The function of the larger, oropharyngeal segment was to further decrease the total ETT resistance. Total lengths of ultrathin-walled ETTs were approximately 1 to 2 cm shorter than the standard ETTs. The ultrathin-walled ETT ID was defined as the ID of the distal, tracheal portion of the tube.

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the study participants. No arrangements have been made for financial reimbursement or commercial production of this novel ETT. The authors wish to thank Drs. Ralph C. Frates, Jr. and Brad Alpert and Jamey Miller, RN, for their suggestions and Mrs. Patsy Sanchez for her secretarial assistance.

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