LABORATORY EVALUATION OF LOW-PRESSURE TRACHEAL TUBE CUFFS: LARGE-VOLUME V. LOW-VOLUME

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Intubation of the trachea with large-volume, low-pressure cuffed tubes provides a tracheal seal at low cuff pressure and is claimed to decrease the possibility of tracheal injury. However, if nitrous oxide is administered, it will diffuse into the air-inflated cuff faster than nitrogen diffuses out, with a consequent increase in cuff pressure (Stanley, Kawamura and Graves, 1974). Moreover, the increase in cuff pressure has been shown to be more rapid in low- than in high-pressure cuffs, the cuff pressure being occasionally as high as 200 mm Hg in low-pressure cuffs (Stanley, 1975). It was reported (Kim, 1980) that the cuff pressure of an air-inflated American HiLo Tracheal Tube increased more rapidly than that of the Shiley Low Pressure Endotracheal Tube when both were exposed to nitrous oxide during clinical anaesthesia. A subsequent study on these two tracheal tubes by other investigators (Kosanin and Maroof, 1981) confirmed this finding.

The present laboratory investigation was conducted to elucidate the factors which may contribute to the more rapid increase in cuff pressure in the large-volume cuffed American HiLo Tracheal Tube. The Intermediate hilo Tracheal Tube was included for comparison.

MATERIALS AND METHODS

Three types of low-pressure cuffed tracheal tubes (10 each) of the same internal diameter (7.0 mm) were studied. The American HiLo tracheal tube (HiLo) represented the large volume, the Intermediate hilo tracheal tube (Inter hilo) the intermediate volume, and the Shiley Low-Pressure endotracheal tube (Shiley) the low-volume cuff. The mock trachea used in the experiment was a 20-ml glass syringe barrel with internal diameter of 20 mm.

To evaluate the performances of each type of cuff, duplicate measurements of the following variables were made using the techniques described.

Compliance of non-intubated cuff (ml/20 cm H₂O). The volume of air released from the non-intubated (i.e. when not in mock trachea) cuff when the cuff pressure was decreased from 40 to 20 cm H₂O. The method of adjusting the different
cuff pressures and measuring volumes is illustrated in detail in figure 1.

Compliance of the intubated cuff (ml/20 cm H₂O). The volume of air released from the intubated cuff when the cuff pressure was decreased from 40 to 20 cm H₂O. The same apparatus and techniques were used as above, except that the tracheal tube was placed in the mock trachea.

Volume of intubated cuff (ml). Following the conclusion of the measurement of compliance of intubated cuff, the volume of the intubated cuff at a cuff pressure of 20 cm H₂O, was measured by aspirating the cuff air into a well-lubricated glass syringe.

Residual volume (ml). After the pressure in the non-intubated cuff was adjusted to 2 cm H₂O using the technique described in figure 1, the cuff volume was measured by aspiration.

Diffusion time (min/20 cm H₂O). The time required to increase the pressure in the intubated cuff from 20 to 40 cm H₂O when 100% nitrous oxide was introduced around the intubated cuff (the technique is described in figure 2).

Specific diffusion rate (ml cm⁻² min⁻¹). The volume of nitrous oxide which diffused through the 1-cm² area of cuff membrane when the area was insufflated with 100% nitrous oxide for 1 min. The technique described in figure 3 measured the volume of nitrous oxide which diffused through the 3.14-cm² area of cuff membrane over 1 h (ml/3.14 cm² h⁻¹). From the measured value, the specific diffusion rate was calculated.

From these measured variables, diffusion rate (volume of nitrous oxide diffused into intubated cuff)
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FIG. 3. Apparatus designed to measure the specific diffusion rate. A syringe barrel (20 ml, 2 cm i.d.) was transsected at the 10-ml marking (5). The calculated area of the open end of transsection (2 cm i.d.) was 3.14 cm². A double folded Latex Tubing (Penrose) (flat size, 1.25" and diameter, 0.75") (4) was wrapped around the outer wall of the transsected syringe barrel as padding. The transsected open end was covered with a cut piece of cuff membrane (2) using a rubber band (3). An air-tight seal between the transsected open end and covered cuff membrane was confirmed by pressurizing the syringe barrel with air under the water. The apparatus was then assembled as shown. The area of cuff membrane covering the transsected open end (3.14 cm²) was insufflated with 100% nitrous oxide 3 litre min⁻¹; delivered through the gas inlet (1) for 1 h. The expanded volume of air was transferred via i.v. extension tubing (7) into the submerged collecting syringe barrel, 3 ml (9) which was prefilled with water. The volume of air trapped in the collecting syringe barrel was measured at the end of 1 h in a manner previously described. (6) = Syringe barrel, 50 ml; (8) = three-way stop-cock; (10) = water reservoir.

cuff in 1 min), surface area (area of intubated cuff available for nitrous oxide diffusion), \( P_t \) (tracheal wall pressure exerted by the intubated cuff), and degree of folding of intubated cuff membrane were derived by the following equations:

\[
\text{Diffusion rate (ml min}^{-1}) = \frac{\text{compliance of intubated cuff (ml/20 cm H}_2\text{O)}}{\text{diffusion time (min/20 cm H}_2\text{O)}}
\]

Surface area available for nitrous oxide diffusion consisted of two areas, the free area (area not in contact with the "tracheal" wall where nitrous oxide contacts freely), and the channelled area (area created by folding of cuff membrane through which nitrous oxide channelling occurs):

\[
\text{Surface area (cm}^2) = \frac{\text{diffusion rate (ml min}^{-1})}{\text{specific diffusion rate (ml cm}^{-2}\text{ min}^{-1})}
\]

Tracheal wall pressure could be calculated from the difference in cuff compliance inside and outside the trachea (Homi et al., 1978):

\[
P_{tw} (\text{cm H}_2\text{O}) = P_{int} - P_{non-int}
\]

\( P_{int} \) = pressure of intubated cuff for the given volume of cuff air; \( P_{non-int} \) pressure of non-intubated cuff for the given volume of cuff air.

In our investigations, the values of \( P_{int} \) were derived from the pressure values obtained from the intubated cuff. The values of the \( P_{non-int} \) can be estimated by comparing the value of the volume of intubated cuff with the value of the residual volume. For example, if the value of the volume of intubated cuff is smaller than the value of the residual volume, the value of \( P_{non-int} \) will be negligible (less than 2 cm H₂O); therefore, the \( P_{tw} \) will be equal to or less than 2 cm H₂O smaller than the indicated cuff pressure. If the value of the volume of intubated cuff is larger than the value of the residual volume, the value of the \( P_{non-int} \) will be significant (more than 2 cm H₂O); therefore, the discrepancy between the \( P_{tw} \) and the indicated cuff pressure will be more than 2 cm H₂O.

Degree of folding. When the large-volume, floppy cuff is inflated in the "trachea", the cuff membrane will fold. The degree of folding relates volume difference between the residual volume and the volume of intubated cuff:

\[
\text{degree of folding } \propto \left( \text{residual volume} - \text{volume of intubated cuff} \right)
\]

In other words, if \( P_{tw} = P_{int} \), the cuff folds. If \( P_{tw} < P_{int} \), the cuff does not fold.

RESULTS

The measured and derived variables for the three types of low-pressure tracheal tube cuffs are summarized in tables I and II; the characteristics of each are described below.

American HiLo Tracheal Tube cuff

When the cuff was inflated outside the "trachea", the compliance was higher than that of the other two tubes. However, once the cuff was inserted to the rigid mock trachea, the compliance decreased substantially. Since the volume of intubated cuff was much less than residual volume, all of the cuff pressure was transmitted to the tracheal wall and the degree of folding should be marked. The short diffusion time was the result of a rapid specific diffusion rate, a high degree of folding and a low compliance of intubated cuff.
TABLE I. Measured variables of three types of low-pressure tracheal tube cuffs (mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Compliance Non-intubated (ml/20 cm H₂O)</th>
<th>Intubated cuff vol. (ml)</th>
<th>Residual volume (ml)</th>
<th>Diffusion time (min/20 cm H₂O)</th>
<th>Specific diffusion rate (ml cm⁻¹ min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiLo</td>
<td>2.5±0.1</td>
<td>0.3±0.1</td>
<td>8.9±0.2</td>
<td>16.7±1.0</td>
<td>7.8±1.2</td>
</tr>
<tr>
<td>Inter hilo</td>
<td>1.9±0.1</td>
<td>0.3±0.1</td>
<td>7.2±0.1</td>
<td>11.9±0.2</td>
<td>11.1±0.5</td>
</tr>
<tr>
<td>Shiley</td>
<td>1.8±0.1</td>
<td>0.7±0.1</td>
<td>8.5±0.2</td>
<td>7.6±0.7</td>
<td>23.6±1.3</td>
</tr>
</tbody>
</table>

Table II. Derived variables of three types of low-pressure tracheal tube cuffs. Pₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉ степени

**Intermediate hilo Tracheal Tube cuff**

In spite of a large difference in the values of compliance of non-intubated cuff between the HiLo and the Inter hilo, the values of compliance of intubated cuffs were identical. The surface area available for nitrous oxide diffusion of the Inter hilo cuff (4.03 cm²) was smaller than the value of the HiLo cuff (5.82 cm²) because the degree of folding was less in the Inter hilo. The smaller surface area of the Inter hilo accounted for the longer diffusion time (11 min) compared with the HiLo cuff (7.8 min). Because the volume of intubated cuff of the Inter hilo was less than the residual volume, all of the cuff pressure, 20 cm H₂O, would be transmitted to the tracheal wall, and the cuff membrane should fold—although the degree of folding was less than with the HiLo cuff. In spite of the similar values for diffusion rate, the diffusion time of the Inter hilo cuff was one-half as short as the Shiley cuff because of the low compliance of intubated cuff of the Inter hilo.

**Shiley Low Pressure Endotracheal Tube cuff**

The Shiley cuff showed the lowest compliance of non-intubated cuff; however, the compliance of intubated cuff was twice as great as the values of the HiLo and the Inter hilo cuffs. This high compliance of intubated cuff could be explained by a large expandable free area. Because the volume of intubated cuff was larger than the residual volume, the tracheal wall pressure was less than the indicated cuff pressure, 20 cm H₂O, and the cuff membrane should not fold. Therefore, the surface area available for nitrous oxide diffusion was limited to the free area not in contact with the tracheal wall. The diffusion time of the Shiley cuff (23.6 min) was almost three times longer than the HiLo (7.8 min), and twice as long as the Inter hilo (11.1 min). Less nitrous oxide diffused through the unit area of the Shiley cuff membrane during 1 min than with the HiLo.

**DISCUSSION**

The materials used in the study were readily available in the operating suite. The designs were simple and could be reproduced easily, yet yielded relatively accurate and useful clinical information. To maintain simplicity, we did not try to correct for minor variations such as change in volume caused by the compression of air, the residual volume was measured at cuff pressure (2 cm H₂O) instead of atmospheric pressure, and the volumes expressed as the volume of cuff included the volume of the pilot balloon. However, these minor
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variations should not alter the interpretation of our results.

We have reported that, when more than 50% nitrous oxide was administered in clinical anaesthesia, the times to double and treble an initial cuff pressure of 20 mm Hg, were 30 and 70 min, respectively for the HiLo tube, and 40 and 130 min, respectively for the Shiley tube. Compared with the Shiley cuff, the HiLo cuff has a large residual volume, a greater surface area, and a thinner cuff membrane (0.033 v. 0.135 mm) (Bernhard, Yost and Turndorf, 1978). These characteristics produce the highest compliance when measured outside the “trachea”. However, when the cuff is inflated inside the rigid mock trachea, a large portion of the surface area of the cuff is in contact with the tracheal wall and loses its elastance. Only that small portion of the surface area which is free of contact with the tracheal wall retains its elastance and is expandable. The compliance of the intubated cuff depends mainly on this expandable free area. The inflated HiLo and Inter hilo cuffs in the trachea adopt a cylindrical shape, and the expandable free area spreads out horizontally. The inflated Shiley cuff resembles a spindle shape, and the expandable free area spreads out less than the horizontal angle. Therefore, the horizontally flared surface area of HiLo cuff has a smaller surface area than the slanted Shiley cuff, accounting for the lower compliance of the former.

The only difference between the Inter hilo and the HiLo cuff is the shorter length of the cuff on the Inter hilo. When these floppy cuffs were inflated in the “trachea”, the expandable free area of cuff became identical, as did the compliance. Our study demonstrated that, in spite of a large difference between these two cuffs in the value of compliance of non-intubated cuff, the difference in compliance was abolished upon intubation.

Diffusion of nitrous oxide into an air-inflated cuff depends on the partial pressure gradient of the nitrous oxide across the cuff membrane, the surface area available for nitrous oxide diffusion, and the specific diffusion rate of nitrous oxide through the cuff membrane.

The diffusion time of the HiLo cuff was less than that of the Inter hilo, despite the fact that both cuffs were made of the same material, had equal expandable free areas and identical values of compliance of intubated cuff. When both floppy cuffs were inflated in the trachea, the cuff membrane folded. The folding could increase the area for diffusion of nitrous oxide, without affecting its compliance. Despite the identical expandable free areas, the surface area available for the diffusion of nitrous oxide in the HiLo cuff was greater than in the Inter hilo cuff because the HiLo cuff had a higher degree of folding. The different cuff volumes between these two cuffs does not seem to affect the diffusion time. During the specific diffusion rate study, we observed no difference in the amount of nitrous oxide diffusing through the unit area of the cuff membrane per hour with cuff volumes of 10 and 20 ml.

When both intubated and non-intubated cuffs are inflated with a given volume of air, the pressure of the intubated cuff will be greater than the non-intubated cuff if the intubated cuff exerts its pressure against the tracheal wall. The difference in pressure between the intubated and non-intubated cuff is the pressure transmitted to the tracheal wall. This relationship was described as $P_{tw} = P_{int} - P_{non-int}$. This equation can also be applied in estimating the degree of folding. If $P_{tw} < P_{int}$, the cuff should not fold.

At the residual volume, the cuff is maximally expanded before being stretched. If the volume of intubated cuff is less than the residual volume, the cuff membrane should fold because the cuff cannot be fully expanded at the volume of intubated cuff. If the volume of intubated cuff exceeds the residual volume, the cuff should not fold because the cuff membrane is already stretched before reaching the volume of intubated cuff. The degree of folding should be related to the difference between the residual volume and the volume of intubated cuff. The surface area available for nitrous oxide diffusion is included in two areas, the expandable free area and the channelled area created by the folding.

Because the residual volumes of the HiLo and Inter hilo cuffs are larger than the volumes of intubated cuff, all of the cuff pressure is transmitted to the tracheal wall and both cuffs fold in the trachea, but the degree of folding was greater with the HiLo cuff. However, the residual volume of the Shiley cuff is less than the volume of intubated cuff; therefore, the estimated tracheal wall pressure is the difference between the intubated cuff pressure, 20 cm H$_2$O, and the non-intubated cuff pressure generated by 8.5 ml of air. In our experimental settings (tracheal tube, 7 mm i.d., inserted to a mock trachea, 20 mm i.d.), the cuff pressure of the Shiley tube (20 cm H$_2$O) may not provide an adequate tracheal seal for positive
pressure ventilation. The large surface area of the Shiley cuff, which represents the expandable free area, accounts for its high compliance of intubated cuff. The diffusion time should be shortened by the large surface area, but it is counteracted by the low specific diffusion rate and the high compliance of intubated cuff. If the Shiley cuff pressure is adjusted to exert the same tracheal wall pressure, 20 cm HgO, as the HiLo and Inter hilo, all measured and derived variables of the Shiley cuff should be different.

Even though the simulated mock trachea used in our laboratory investigation is quite different from the human trachea, the study seems to yield logical answers to the questions raised during our previous study in patients (Kim, 1980).

When low-pressure cuffed tracheal tubes are used for short-term intubation, conclusive clinical evidence of the superiority of one type of tracheal tube over another (Stanley, 1975; Homi et al., 1978) or of serious tracheal damage caused by overinflation of the cuff is lacking. However, it may be still good practice to maintain tracheal wall pressure low while maintaining a seal, because minor injury to the tracheal mucosa and deterioration of the compliance of tracheal muscle (Leverment, Pearson and Rae, 1975) can be caused by overinflation of the cuff (Dobrin and Canfield, 1977; Nordin, Lindholm and Wolgast, 1977). In addition, attention to tracheal wall pressure may prevent other complications such as the herniation of the cuff (Ward, Gamel and Benumof, 1978), or the collapse of the lumen of the tracheal tube (Perel et al., 1977). If the pressure injury occurs with the overinflated large-volume cuff, a wider area of tracheal mucosa or localized areas under the folds are vulnerable. Unavoidable folding with the large-volume cuff cannot only be a potential source of tracheal aspiration (Pavlin, VanNimwegan and Hornbein, 1975; Bernhard et al., 1979) but may also provide additional surface area for the diffusion of nitrous oxide. The main advantage claimed by those who advocate large-volume, low-pressure tracheal tubes is that a tracheal seal can be obtained with a low cuff pressure, since the cuff deforms to conform to the shape of the trachea (Crawley and Cross, 1975). This claim should be valid as long as the cuff pressure is low. However, without proper control of cuff pressure during anaesthesia, a dangerously high tracheal wall pressure can build up in a shorter time with this type of large-volume cuff than with the low-volume cuff.

In conclusion, we found no evidence from this laboratory investigation to support the superiority of the large-volume, low-pressure over the low-volume, low-pressure cuffed tracheal tube. The selection of tracheal tube cuffs cannot replace the preventive measures against overinflation of the cuff during anaesthesia. We believe that specification of the residual volume for each tracheal tube cuff would give meaningful information regarding the nature and expected performance of the cuff when in the trachea, and some indication of the relationship between cuff pressure and tracheal wall pressure.

REFERENCES


