A STUDY OF INFLATABLE CUFFS ON ENDOTRACHEAL TUBES

Pressures exerted on the trachea

C. F. MACKENZIE, S. KLOSE AND D. R. G. BROWNE

SUMMARY

A simple method of measuring the pressure exerted by the cuff of an endotracheal tube on the trachea is described and has been used to measure the pressures exerted by 16 commercially available cuffs on the wall of a model trachea. The Shiley, Portex soft-seal, Kamen-Wilkinson (Bivona Fome) tubes had the lowest tracheal wall pressures. Using this method in vivo the changes in tracheal wall pressure exerted by a low-pressure cuff during percussion and vibration physiotherapy, and when the patient "fights the ventilator", were recorded.

Tracheal stenosis is a major long-term problem of prolonged endotracheal intubation (Cooper and Grillo, 1969). Amongst the causative factors, in addition to repeated and prolonged intubation, are the material, size and shape of the endotracheal cuff (Lunding, 1964; Guess and Stetson, 1968; Crawley and Cross, 1975), inadequate patient sedation, high ventilator pressures including repeated tube movement during ventilation (Davidson et al., 1971) and the pressure exerted on the trachea by the cuffed endotracheal tube (Cooper and Grillo, 1969; Hilding, 1971).

There is a greater incidence of tracheal stenosis in patients with pre-existing lung disease and when infection of the respiratory tract occurs (notably with Pseudomonas aeruginosa, P. pyocyanea, Klebsiella aerogenes, Staphylococcus aureus, and coliform bacilli). Steroid therapy predisposes to uncontrolled airway infection and exaggeration of the tracheal injury (Hedden, Ersoz and Safar, 1969; Andrews and Pearson, 1973). There is also an increased likelihood of tracheal stenosis when hypotensive episodes complicate renal dialysis, tetanus, polyneuritis and cardiothoracic bypass (Adriani and Phillips, 1957; Bassett, 1971).

Many of these factors are unavoidable, but great advances have been made recently in the use of "floppy" cuffs on endotracheal tubes, with the intention of reducing the pressure exerted on the trachea to a value that does not exceed the capillary pressure ($P_{cap}$) in the tracheal mucosa under the cuff.

At the arteriolar end of the capillary, $P_{cap}$ is 32 mm Hg (Ganong, 1973). Pathological changes have been noted in the tracheal mucosa of patients in whom the trachea has been intubated for as little as 2 hr (Dwyer, Kronenberg and Saklad, 1949; Bowes, Kelly and Peacock, 1973). The pressure exerted by the cuff on the trachea has been incriminated as the most important avoidable factor (Cooper and Grillo, 1969). For this reason, and to allow selection of a suitable cuff, we have devised a simple method of measuring this pressure.

**PRINCIPLE**

The pressure in the cuff of a freely suspended endotracheal tube was measured ($P_{skin}$) after 1-ml increments of air had been injected into the cuff (fig. 1) and a pressure/volume curve was plotted.

The same endotracheal tube was inserted into the barrel of a 20-ml syringe and the cuff was inflated just to prevent a leak when the airway pressure was 40 cm H$_2$O. The volume of air injected into the cuff

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and the pressure in the cuff ($p_{\text{cuff}}$) were recorded (fig. 2).

The pressure ($p_T$) exerted on the syringe barrel was given by:

$$p_T = p_{\text{cuff}} - p_{\text{skin}}$$

when both $p_{\text{cuff}}$ and $p_{\text{skin}}$ were measured with the same volume of air in the cuff.

METHOD

An endotracheal tube was warmed for 2 hr at 37 °C then suspended freely, and 1-ml increments of air were injected through a leak-proof three-way tap into the cuff (fig. 1). The pressure was recorded after each additional increment of air by means of a Hewlett-Packard transducer (1280) connected to a Pressure Module (Hewlett-Packard 78205A) and a pressure/volume curve was plotted for that particular endotracheal tube. This was a measure of the elastic property of the cuff and was a function of the cuff diameter (Crawley and Cross, 1975).

In order to obtain the pressure that any given cuff exerts on the trachea ($p_T$) one must subtract the pressure resulting from the elastic property of the cuff ($p_{\text{skin}}$) from the pressure which was recorded in the cuff ($p_{\text{cuff}}$) when it was inflated to the point just preventing a leak (seal point).

$p_{\text{cuff}}$ was measured in the same manner as $p_{\text{skin}}$ except that a 20-ml syringe barrel was used to simulate a human trachea (fig. 2). The endotracheal cuff was inserted into the syringe barrel and inflated to the seal point whilst being "ventilated" at up to 40 cm H$_2$O pressure. The pressure in the cuff ($p_{\text{cuff}}$) was then recorded.

RESULTS

$p_{\text{skin}}$ in 9.0-mm tubes

The results are summarized in figure 3, showing the intracuff pressure/volume characteristics. It can be seen that the cuff characteristics of the tubes are in two groups: high-pressure and low-pressure. The low-pressure group comprises the Eschmann fluted cuff, the Portex soft-seal and pre-stretched cuffs (Geffin and Pontoppiddan, 1969) and the Kamen-Wilkinson (Bivona Fome).

$p_T$ of the 16 cuffs in a model trachea: the choice of tube

Table I shows the pressure exerted by the cuffs on the model trachea at the seal point

$$p_T = p_{\text{cuff}} - p_{\text{skin}}.$$
The tubes are again in two groups: those having their seal points below $p_{\text{cap}}$ (32 mm Hg at the arteriolar end of the capillary) and those whose seal point is above this value. It should be noted that it was impossible to measure $p_T$ for the Rüsch and Franklin cuffs (table I: "no seal" in final column) because the intracuff pressure required to reach seal point exceeded the limits of our recording apparatus (350 mm Hg).

The large volume floppy cuffs such as the Portex soft-seal have no elastic properties when inflated with volumes of air normally required to obtain a seal. Therefore $p_{\text{skin}}$ was zero, and $p_{\text{cuff}}$ equals $p_T$. The three cuffs whose seal points were below $p_{\text{cap}}$ are the Kamen–Wilkinson (Bivona Fome), the Portex soft-seal and the Shiley. In view of these findings, it was felt that it was justifiable to use only one of these tubes for all clinical investigations, and the Portex soft-seal tube was chosen.

The effect of cuff inflation beyond seal point

Figure 4 shows that once a seal point (open star) had been achieved, the addition of small increments of air produced marked increases in $p_T$. It can be seen that, even with the Portex soft-seal and Kamen–Wilkinson cuffs, inflation with 1 ml of air beyond the seal point caused $p_T$ to exceed $p_{\text{cap}}$ (fig. 4).

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**TABLE I. Pressure exerted by the cuffs on the model trachea at seal points**

<table>
<thead>
<tr>
<th>Make of tube</th>
<th>Volume of air to prevent leak (ml)</th>
<th>$p_{\text{skin}}$ 37 °C (mm Hg)</th>
<th>$p_{\text{cuff}}$ 37 °C (mm Hg)</th>
<th>$p_T$ seal point (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamen–Wilkinson (Bivona Fome)</td>
<td>2</td>
<td>3</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>Warne (Low-pressure cuff)</td>
<td>10</td>
<td>199</td>
<td>277</td>
<td>78</td>
</tr>
<tr>
<td>Eschmann (Fluted cuff)</td>
<td>9</td>
<td>23</td>
<td>224</td>
<td>201</td>
</tr>
<tr>
<td>Franklin (Clearway)</td>
<td>10</td>
<td>277</td>
<td>278</td>
<td>No seal</td>
</tr>
<tr>
<td>Shiley (Low-pressure cuff)</td>
<td>5</td>
<td>61</td>
<td>73</td>
<td>12</td>
</tr>
<tr>
<td>Rüsch (Tracheostomy tube)</td>
<td>6</td>
<td>292</td>
<td>338</td>
<td>No seal</td>
</tr>
<tr>
<td>Eschmann</td>
<td>10</td>
<td>290</td>
<td>347</td>
<td>57</td>
</tr>
<tr>
<td>B.O.C. (Implant tested)</td>
<td>12</td>
<td>205</td>
<td>279</td>
<td>74</td>
</tr>
<tr>
<td>B.O.C. Magill (New red rubber tube)</td>
<td>11</td>
<td>165</td>
<td>209</td>
<td>44</td>
</tr>
<tr>
<td>B.O.C. Magill (Used red rubber tube)</td>
<td>10</td>
<td>91</td>
<td>125</td>
<td>34</td>
</tr>
<tr>
<td>B.O.C. Latex</td>
<td>10</td>
<td>198</td>
<td>244</td>
<td>46</td>
</tr>
<tr>
<td>B.O.C. Oxford (Red rubber)</td>
<td>8</td>
<td>132</td>
<td>201</td>
<td>69</td>
</tr>
<tr>
<td>Portex</td>
<td>10</td>
<td>273</td>
<td>325</td>
<td>52</td>
</tr>
<tr>
<td>Portex (Blue line)</td>
<td>8</td>
<td>171</td>
<td>234</td>
<td>63</td>
</tr>
<tr>
<td>Portex (Blue line, pre-stretched)</td>
<td>8</td>
<td>0</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Portex (Soft-seal)</td>
<td>4</td>
<td>0</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

**FIG. 4. Pressure/volume curves showing the effect of exceeding the seal point (open star).**
The effects of physiotherapy upon pT in the Portex
low-pressure cuffed tube

The effects of two types of physiotherapy (vibration and "bagging") and of positive pressure ventilation (volume cycled ventilator) on pT in a sedated relaxed patient were compared (figs. 5 and 6).

![Graph showing the effects of physiotherapy on pT](image1)

**Fig. 5.** Comparison of cuff pressures during IPPV and during vibration physiotherapy.

![Graph showing the effects of "bagging" on pT](image2)

**Fig. 6.** The effect on cuff pressure of "bagging."

The initial pT of the cuff was 11 mm Hg and this increased to 25 mm Hg during the inspiratory phase of the ventilator with an inflation pressure of 35 cm H2O. During the process of bagging (600–800 ml) pT increased to 42 mm Hg, and during vibration pT reached a maximum of 170 mm Hg on several occasions.

**The effects on pT when a patient "fights the ventilator"**

An increase in pT from 22 to 81 mm Hg was observed during the patient’s resistance (fig. 7), and, as can be seen from the tracing, pT exceeded pCOP consistently when the patient “fought the ventilator”.

![Graph showing the effects of resistance on pT](image3)

**Fig. 7.** The effect on cuff pressure of “fighting the ventilator”.

DISCUSSION

Previous methods of measuring the pressure exerted by an endotracheal cuff on the trachea have depended on interposing a balloon-like structure between the cuff and the tracheal wall and then measuring the pressure in this balloon (Muir and Stratton, 1954; Knowlson and Bassett, 1970; Hilding, 1971; Kamen and Wilkinson, 1971). Alternatively, by placing pressure transducers in the wall of either a model or a human trachea postmortem, the pressure exerted by the cuff can be measured (Adriani and Phillips, 1957; Lomholt, 1967; Carroll, Hedden and Safar, 1969; Wu et al., 1973).

The balloon method has the obvious disadvantage that it can be used only on those patients in whom the specially constructed tube has been passed. In addition to the likelihood of the balloon becoming displaced it is difficult to maintain an airtight seal. Anything interposed between the cuff and the trachea (a balloon, an envelope or a transducer) will distort both the cuff and the trachea, resulting in an artificial reading of the pressure. The other methods, using transducers in the wall of the trachea, cannot be used in the intubated patient.

The method described does not require a specially constructed tube to be passed, and can be used for continuous monitoring or for occasional checks on the pressure exerted by the cuff on the trachea in any intubated patient. It is a dynamic method so that if the cuff is over-inflated it will measure the increase in pressure beyond the seal point, unlike the static pressure measurement of other methods (Muir and Stratton, 1954; Knowlson and Bassett, 1970; Hilding, 1971; Wu et al., 1973).

When measuring pskin it was found that the Eschmann fluted cuff and the Portex pre-stretched cuff both showed all the characteristics of a low-pressure cuff; but when they were inserted into the model trachea pT was 201 and 58 mm Hg respectively. A possible explanation is that the fluted cuff has a ribbed framework which requires a large volume of air to overcome leakage at high inflation pressures.
(40 cm H₂O). The pre-stretched cuff tends to fold within the model trachea because it has such a large volume when pre-stretched to 20–30 ml at 90–95 °C (Geffin and Pontoppiddan, 1969) and leakage occurs readily along the folds.

Only three cuffs exerted pressures less than \( p_{\text{cap}} \) at the seal point and we feel that a choice of these tubes should be made in clinical situations in which prolonged intubation is anticipated.

The increase in \( p_T \) beyond \( p_{\text{cap}} \) when small increments of air are inflated into the cuff at the seal point emphasizes that it is hazardous to over-inflate any cuff beyond the seal point.

There was a marked increase in \( p_T \) during both bagging and vibration physiotherapy using the Portex soft-seal cuff. This increase is momentary during the actual procedure. We believe that, if these manoeuvres are performed for short periods only, they will not cause ischaemic damage to the tracheal mucosa.

However when the patient fights the ventilator (fig. 7) \( p_T \) exceeds \( p_{\text{cap}} \). Thus a prolonged episode of this type would be damaging to the mucosa.

Accurate measurements of the initial volume used for inflating the cuff and the size and make of the tube must be recorded on the patient's chart. If it appears necessary to add further volumes to maintain a seal, this must be investigated bearing in mind causes such as a leaking cuff, decreased lung compliance necessitating higher ventilator pressures, or a progressively dilating trachea.

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REFERENCES


ETUDE SUR LES MANCHONS GONFLABLES DES TUBES ENDOTRACHEAUX: PRESSION EXERCEE SUR LA TRACHEE

RESUME
On décrit dans cet article une méthode simple pour mesurer la pression exercée par le manchon d’un tube endotrachéal sur la trachée. Cette méthode a été utilisée pour mesurer les pressions exercées sur les parois d’un modèle de trachée par 16 types de manchons que l’on trouve dans le commerce. Les tubes Shiley, Portex soft-seal (à joint souple) et Kamen–Wilkinson (Bivona Fome) ont exercé les pressions les plus faibles sur les parois de la trachée. En utilisant cette méthode *in vivo*, on a enregistré les variations de la pression exercée sur les parois de la trachée par un manchon à basse pression pendant la physiothérapie par percussion et vibrations et lorsque le patient "lutte contre le ventilateur".

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Se describe un método sencillo para medir la presión ejercida por las manillas de un tubo endotraqueal sobre la tráquea y se ha utilizado para medir las presiones ejercidas por 16 manillas comercialmente asequibles, sobre la pared de una tráquea de muestra. Los tubos Shiley, Portex de cierre blando, Kamen-Wilkinson (Bivona Fome) son los que ejercen menor presión traqueal. Usando este método \textit{in vivo} se registraron los cambios en la presión de las paredes traqueales ejercidas por una manilla de baja presión durante la fisioterapia de percusión y vibración, y cuando el paciente "lucha contra el ventilador".