A METHOD FOR COMPARING ENDOTRACHEAL CUFFS

A controlled study of tracheal trauma in dogs

J. HOMI, W. NOTCUTT, J. J. JONES AND B. R. SPARKE

SUMMARY

Damage to the trachea produced in dogs by large and small residual volume cuffs during 6 h of IPPV was compared using a specially designed endotracheal tube. The cuffs under evaluation were adjusted to exert similar average pressures on the tracheal wall, so that many of the variables believed responsible for tracheal injury were controlled. The true compliance of the cuff was measured with the tube inside and outside the trachea of the anaesthetized dogs. The maximum estimated pressure transmitted to the tracheal wall, derived from these compliance curves, was found to equal the peak airway pressure in the presence of a small air leak past each cuff. At various tracheal wall pressures there were only very minor differences in tracheal damage between the large and small residual volume cuffs tested.

Despite the introduction of many types of large residual volume endotracheal cuffs (Lomholt, 1967; Grillo et al., 1971; Kamen and Wilkinson, 1971) reports of tracheal damage continue to appear (Paegle, Ayres and Davis, 1973; Kaliner et al., 1975; Bradbeer et al., 1976). Furthermore, in many centres, small residual volume cuffs are still in use (Griffiths, 1976; Powaser et al., 1976) particularly for short periods of artificial ventilation. Various factors other than the type of cuff may cause injury to the trachea (Crawley and Cross, 1975) yet few controlled comparisons between cuffs in the same experimental animal are documented. Using a specially designed double-lumen, double-cuff, tube under controlled conditions, an assessment was made of the tracheal damage produced in dogs when the cuffs were exerting the same average pressure on the mucosa for the same time interval.

METHODS

The specially designed double-lumen, double-cuff, tracheal tube (fig. 1) incorporated the low residual volume cuff of a Magill red rubber tube (Medishield) as the lower cuff and the high residual volume cuff of a p.v.c. tracheostomy tube (Portex—Blue Line Soft-seal) as the upper cuff. This combination was considered to represent two extremes of cuff design amongst commonly used cuffs. Both cuffs were exposed to the airway pressure changes that occur during the respiratory cycle, by passing the ventilating air down the outer lumen of the tube and, via the ventilation ports, into the space between the cuffs. Changes in the amount of air leaking past the cuffs could be detected during the experiment and cuff pressures could be adjusted, when necessary, to maintain a constant tracheal wall pressure.

Pressures inside each cuff were measured using Statham P 23 AC transducers (calibrated against a mercury manometer) and recorded using a Grass Polygraph Model No. 79D. Compliance curves for each cuff were made, with the tube freely suspended in air and also inside the trachea of an anaesthetized dog. Corrections were made for the compression of air in the inflating syringe, pressure transducer and connection tubing (Appendix 1). Cuff-to-wall pressures could be calculated from the difference in cuff compliance inside and outside the trachea.

Adult mongrel dogs (10-27 kg; mean a.p. tracheal diameter 16.7 mm, range 14–22 mm) were anaesthetized with sodium pentobarbitone. The trachea was intubated, the tube fixed in place and the lungs ventilated with a constant volume Palmer Ideal Pump at a fixed rate. The compliance curve for each cuff in the trachea was obtained and the cuffs were inflated to exert the same average pressure on the trachea for the same time interval.

FIG. 1. Diagrammatic representation of the double-lumen, double-cuff, endotracheal tube used to compare a small residual volume, red rubber cuff and a large residual volume, polyvinyl cuff. Details of design, construction and method of use can be obtained from the authors.

FIG. 2. Diagram of the experimental arrangement for recording and controlling the average pressure exerted by the cuffs during IPPV and for physiological monitoring of the dog.
The femoral artery and femoral vein were cannulated for arterial pressure recording, arterial blood-gas analysis and drug administration. The right axillary artery was cannulated and a catheter introduced to lie in the brachiophenalic artery near the aortic root (fig. 2). A typical set of recordings is shown in figure 3.

$P_{a}O_{2}$ and $P_{a}CO_{2}$ were checked periodically and ventilation altered where necessary, either by introducing a deadspace, or by adjusting the tidal volume. After 6 h (mean) the experiments were concluded. Disulphine blue 0.2 ml kg$^{-1}$ was injected i.v. One minute later 20 ml of a suspension of iron oxide was injected via the catheter in the brachiocephalic artery to form emboli in the arterioles and capillaries of the trachea. Immediately afterwards 20 ml of a saturated solution of potassium chloride was injected i.v. to produce circulatory arrest.

Dissection of the trachea was performed after the length of the trachea and the position of the tube relative to the carina had been recorded. The tube was then removed, the diameters of the trachea measured with dividers and the trachea excised with its main bronchi. It was opened longitudinally along the posterior wall, irrigated gently to remove excess mucus, and displayed at its original length for identification of the cuff sites. Colour photographs were taken of the trachea, and close-up views of each cuff site.

The trachea was sectioned transversely (fig. 4). The sections were fixed in Bouin’s solution for about 24 h, trimmed and processed in preparation for histological staining (haematoxylin and eosin and Perl’s stain for iron).

**RESULTS**

**Cuff pressure on tracheal wall**

The corrected compliance curves (Appendix I) for each cuff inside and outside the trachea were found to correlate almost exactly with compliance curves constructed when water was used instead of air for inflating the cuffs. The pressure exerted on the tracheal wall could thus be calculated from these curves by measuring the difference in the cuff pressures for a given injected volume of air or water. The average calculated tracheal wall pressure was equal to the airway pressure in the presence of a small air leak (up to 20% of expired volume) past a cuff (fig. 5). During IPPV, as the cuff was inflated it expanded to fill the trachea and thus diminish the air leak. When it exerted pressure on the tracheal wall, the leak diminished rapidly, more of the tidal volume being used to inflate the lungs; consequently, the airway pressure increased. When the trachea was sealed the airway pressure increased no further, but the tracheal wall pressure would increase if the cuff were inflated further. Thus, from “touch” to “occlude” (fig. 5) the airway pressure was found to equal the calculated tracheal wall pressure.

**Tracheal blood flow**

Photography. The trachea at each cuff site was graded according to the degree of mucosal blanching (lack of green colouration produced by disulphine blue). The mucosa over cartilage was compared with undisturbed tracheal mucosa (table I). No pallor was seen between the rings. Student’s $t$ test was applied to the difference in pallor produced by pairs of cuffs in each dog. No significant difference was found ($n = 21$, $t = 1.04$, $P > 0.2$).

The results for the pallor produced at different tracheal wall pressures by both cuffs between 4 and 115 mm Hg were combined (table II). There was an abrupt increase in the degree of pallor at wall pressures between 30 and 40 mm Hg. A cumulative sum (Cusum) technique was used on the data (Chaput de Saintonge and Vere, 1974) and this showed that an almost constant degree of pallor occurred at wall pressures less than 35 mm Hg, and that a greater but also constant degree of pallor occurred at pressures greater than this value (33 mm Hg is the average pressure one would expect to find at the arteriolar end of the capillary bed within the normal range of systemic arterial pressure).

Every cuff site showed a reduction in the number of visible blood vessels, particularly those overlaying the cartilages. However, our technique did not have sufficient discrimination to justify statistical analysis.

Histology. The sections of trachea prepared with Perl’s stain were examined by B.R.S. The iron oxide particles were stained with Prussian blue so that the vessels could be identified easily. The number of vessels in the mucosa over the cartilage which contained iron were counted and expressed as a fraction of the number seen in a section from the undisturbed part of the trachea see (table I). There was no significant difference between each pair of cuffs ($t = 0.59$; $P > 0.2$). No relationship to tracheal wall pressure could be found and it appeared that “blood flow” as determined by this technique was greater at some cuff sites than in control areas.

**Tracheal damage**

Photographs. The close-up slides were examined for the presence of petecchial haemorrhages at the
TABLE I. “D” refers to the lower cuff (red rubber, low residual volume) and “F” refers to the upper cuff (p.v.c., high residual volume)

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<th>Dog no.</th>
<th>Average pressure on tracheal wall (mm Hg)</th>
<th>Tidal volume (ml)</th>
<th>Pallor* (grades 1-4)</th>
<th>Petecchiae† (grades 0-3)</th>
<th>Vessels‡ (Perl’s stain)</th>
<th>Damage§ “A” (%)</th>
<th>Damage§ “B” (%)</th>
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Pair differences: $n = 21$ (Student’s $t = 1.25$), $n = 21$ (Student’s $t = 1.04$), $n = 12$ (Student’s $t = 0.25$), $n = 17$ (Student’s $t = 0.59$), $n = 21$ (Student’s $t = 1.43$), $n = 21$ (Student’s $t = 0.96$)

| * Pallor grade: 1 = <25%, 2 = <50%, 3 = <75%, 4 = <100%.
| † Petecchiae grade: 0 = none, 1 = mild, 2 = moderate, 3 = severe.
| ‡ The number of vessels under each cuff section is expressed as a fraction of the number found in a control section.
| § Damage: The percentage of the circumference damaged.

TABLE II. Degree of pallor produced at the cuff site at different tracheal wall pressures ($P_{TW} = \text{cuff to tracheal wall pressure (mm Hg)}$). Results for both cuffs have been combined

<table>
<thead>
<tr>
<th>Pallor</th>
<th>$P_{TW}$</th>
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<td>&lt;100%</td>
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<td>&lt;75%</td>
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<td>&lt;25%</td>
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cuff sites and graded according to severity. Sixty-six per cent of cuff sites examined showed haemorrhage (table I). However, there was no significant difference between pairs of cuffs ($n = 12$, $t = 0.25$, $P > 0.5$). No relationship to tracheal wall pressure or tidal volume could be demonstrated.

Histology. The haematoxylin and eosin sections of trachea were examined by B.R.S. The mucosal damage was graded (fig. 6). The circumference of the mucosal surface was measured with a planimeter. The length of mucosal damage was measured and expressed as a percentage of the total circumference of the section. This included damage at all levels except that of the cilia which was not assessed (table II, Damage “A”). The percentage of the circumference eroded to a deeper level than the surface layer of columnar cells was measured (table I, Damage “B”). There was no evidence of trauma to the lamina propria (basement membrane), or cartilage in any section. The difference in damage produced by each pair of cuffs was analysed and was not significant (“A”: $t = 1.43$, $P = 0.1$; “B”: $t = 0.96$, $P > 0.2$). When the epithelial damage was compared with the tracheal wall pressure, no relationship could be demonstrated.

To examine the effect of friction on mucosal damage 18 cuff sites were paired for similar pressures and types of cuff but with different tidal volumes (500 ml...
Polymorphonuclear infiltration was found on nearly every section of trachea including sections from control areas and both bronchi. Sections of trachea and bronchi from two control dogs that were not intubated, however, showed no infiltration or inflammatory exudate.

**DISCUSSION**

**Pressure on tracheal wall**

The pressure exerted on the tracheal mucosa by endotracheal cuffs is difficult to measure, particularly...
without producing injury to the mucosa or changing the blood flow and physical properties of the trachea. Implanted transducers, and balloons interposed between the wall of the trachea and the cuff, are examples of such methods (Hilding, 1971; Wu et al., 1973; Dobrin and Canfield, 1977). An indirect method described by Dobrin, Goldberg and Canfield (1974) would result in mucosal trauma as a result of withdrawing the tube from the trachea with the cuff inflated. Another indirect method of estimating tracheal wall pressure, using a syringe barrel as a model trachea, assumes that the compliance of each trachea is the same as that of a rigid tube (MacKenzie, Klose and Browne, 1976). These workers also failed to take into account the compression of gas in the recording system, pilot tube and syringe, which is important, in the case of small residual volume cuffs, in describing accurate compliance curves. On the other hand, they emphasized temperature equilibrium during the experiment, which is less important (Appendix 1). The compliance curves for small residual volume cuffs obtained using mercury manometers (Ching and Nealon, 1974; Powaser et al., 1976) also failed to allow for the large compression and displacement volumes in the recording system. Our compliance curves were identical to those obtained by inflating the cuff and recording system with water, which is incompressible.

The compliance curves for large residual volume cuffs showed that the pressure transmitted to the tracheal wall followed closely the intra-cuff pressure up to but not beyond the residual volume of the cuff. When the circumference of this cuff exceeded that of the trachea, folds occurred which prevented a gastight seal, except at intra-cuff pressures in excess of
peak airway pressure. When a complete seal was achieved a high pressure was transmitted to the tracheal wall, particularly along any folds or ridges in the cuff (Cross, 1973). The deliberate use of a measured air leak past each cuff at peak lung inflation enables cuffs to be compared while exerting similar average pressures on the trachea and is, to our knowledge, a new method of comparing cuffs. The rationale based on the similarity to a Starling resistor is explained in Appendix 2 and figure 7. This method would seem preferable to sealing the trachea against a high continuous airway pressure (Dobrin and Canfield, 1977) which would tend to produce very great tracheal mucosal pressures and dilate the trachea.

The double-lumen design of our experimental tube provides a communicating space between the two cuffs so that both cuffs are exposed to pressure changes during the respiratory cycle, monitoring and measurement of gas leak past either cuff can be carried out and the pressure in either cuff can be adjusted independently. The single-lumen, double-cuffed tube illustrated by King, Mandava and Kamen (1975) does not offer these features, and alterations in the volume of the cuffs by gas diffusion (Stanley, 1975; Revenas and Lindholm, 1976) and the resulting increased pressure transmitted to the tracheal wall would pass undetected.

**Tracheal damage**

Photography of the excised trachea is technically difficult because of its curvature. This can be overcome largely by opening the trachea anteriorly. However, this makes histological sections unsatisfactory and damages the mucosa overlying the anterior part of the cartilage. Close-up photographs are even more difficult and probably require more sophisticated equipment than was available to us. Photographs did not help to detect the mucosal damage under the cuff site as visible ulceration did not occur in our experiments.

The assessment of damage to the mucosa by examining histological slides seemed to be a satisfactory method of assessment and our findings were similar to those of Bowes, Kelly and Peacock (1973). The lack of any relationship of epithelial damage to pressure may indicate that friction is more important in the production of mucosal damage in relatively short-term ventilation. Although no significant differences in the degree of trauma between cuff sites could be demonstrated there were differences between dogs. Presumably this represented differences in individual susceptibility to trauma.

**Blood flow**

Disulphine blue has been used to delineate areas of devitalized skin, especially in burned patients. It seemed to provide a method of assessing capillary blood in the mucosa over the tracheal cartilages and a relationship to pressure exerted by the cuffs was found. The use of iron particles of variable diameter (5–20 mm), in the absence of microspheres for embolization of the arterial tree, produced results which were difficult to interpret, as particles were seen in the deeper vessels under every cuff. However, embolization produced a transient increase in arterial pressure which may have forced the iron particles into the vessels beneath the cuff. Does the presence of embolic material in the blood vessel represent blood flow, or the obstruction of the vessel distal to the particle? Those authors using microspheres (Nordin,
Applying the gas law: \[ PV = nRT \]

Therefore:

\[ nR = \frac{(PV)}{T} \]

\[ = \frac{(P_0 V_{SO})/T_0 + (P_0 V_{IO})/T_0}{T_0} \]

\[ = \frac{(P_1 V_{SI})/T_0 + (P_1 V_{II})/T_0 + (P_1 V_{CI})/T_1}{T_1} \]

\[ = \frac{(P_1 V_{SI})/T_0 + (P_1 V_{II})/T_0}{T_1} \]

Therefore

\[ \frac{(P_1 V_{SI})/T_0 + (P_1 V_{II})/T_0 + (P_1 V_{CI})/T_1}{T_1} = \frac{(P_1 V_{SI})/T_0 + (P_1 V_{II})/T_0}{T_0} \]

Therefore

\[ V_{C1} = \frac{(V_{SI} - V_{SI})}{T_1/T_0} \]

The correction for the change of temperature of air entering the cuff is about 5%, whereas the correction for the decrease in volume of air as the pressure increases and for the compliance of the tubing and transducers is about 50%.

The correct compliance of the cuff is \[ V_{C1}/(P_1-P_0) \]. This is considerably less than \[ (V_{SO} - V_{SI})/(P_1-P_0) \].

Place the endotracheal tube in the trachea and repeat. Let \[ P_3 V_{SI}, V_{C3} \] and \[ V_{S4} \] correspond to \[ P_1, V_{SI}, V_{C1}, \] and \[ V_{SI} \]. Then

\[ V_{C3} = \frac{(V_{S4} - V_{SI})}{T_1/T_0} \]

The correct compliance of the combined cuff and trachea is \[ V_{C3}/(P_3-P_0) \]. Make \[ V_{C3} = V_{C1} \] that is, inflate the cuff to the same volume inside the trachea as its volume when supported in air. Then the excess pressure in the cuff when inflated to the same volume inside the trachea is \[ P_3 - P_1 \].

\[ V_{C4} = \text{volume of cuff when it first makes contact with the tracheal mucosa (that is, touch volume).} \]

\[ P_4 = \text{pressure in cuff at} \ V_{C4}. \]

Inflate the cuff so that \[ V_{C1} = V_{C3} \] and \[ V_{C4} \], that is so that it has the same volume inflated in air as it has in the trachea and the volume is greater than the “touch” volume.

\[ C_0 = \text{compliance of cuff when inflated from} \ V_{C4} \text{ to} \ V_{C1}. \]

\[ C_T = \text{compliance of trachea when its volume is increased from} \ V_{C4} \text{ to} \ V_{C1}. \]

\[ C_0 = \text{combined compliance of cuff and trachea when cuff is inflated from} \ V_{C4} \text{ to} \ V_{C1}. \]

Then

\[ 1/C_0 = 1/C_T + 1/C_T \]

Therefore

\[ (P_3 - P_1)/(V_{C1} - V_{C4}) = (P_1 - P_4)/(V_{C1} - V_{C4}) + 1/C_T \]

Therefore

\[ 1/C_T = (P_3 - P_4)/(V_{C1} - V_{C4}) \]

Therefore

\[ P_3 - P_1 = (V_{C1} - V_{C4})/C_T \]
Therefore the increase of pressure on the inner surface of the trachea required to increase its volume from $V_{C4}$ (touch volume) to $V_{C1}$ (volume of the inflated cuff) is $P_3 - P_1$.

At $V_{C4}$ (touch volume), the pressure on the inner surface of the trachea is $P_0$. Therefore the wall pressure exerted by the cuff on the tracheal mucosa when the cuff is inflated to $V_{C1}$ is $P_3 - P_1$. The correct wall pressure ($P_3 - P_1$) is considerably greater than the pressure calculated by the method described by Mackenzie, Klose and Brown (1976) which makes no correction for the decrease in the volume of air as it is compressed: When $V_{C3} < V_{C4}$, then $V_{C3} = V_{C1}$ because the air is compressed. Therefore the pressure in the cuff is lower than the pressure when $V_{C3} = V_{C1}$ because the cuff is only partly inflated. Consequently, the wall pressure is underestimated.

APPENDIX 2

A Starling resistor (fig. 7) (Patterson and Starling, 1914) can be represented by two membranes in contact by a pressure $P_R$. $P_A = pressure of fluid on the high pressure side of the resistor. When $P_R > P_A$, the membranes are in contact and there is no flow. When $P_A > P_R$, the membranes are forced apart and there is more flow and consequently $P_A$ decreases. Equilibrium is reached when $P_A = P_R$ and flow becomes constant. When fluid is passing through the Starling resistor, the pressure on the high pressure side is stabilized and is equal to $P_R$.

The cuff inflated inside the trachea behaves as a Starling resistor. When $P_{AW} = P_{TW}$ there is no flow (leak) past the cuff. When there is a steady flow (leak) past the cuff $P_{AW} = P_{TW}$. When air is leaking past the cuff, the pressure exerted by the air on the tracheal mucosa and on the surface of the cuff is the airway pressure ($P_{AW}$) and is equal to the wall pressure ($P_{TW}$). The airway pressure is also transmitted through the cuff to the tracheal mucosa in contact with the cuff. If, at any point, the pressure exerted by the cuff on the tracheal mucosa becomes greater than $P_{AW}$ air flow past the cuff will cease. Consequently, the mean pressure exerted by the cuff on the tracheal mucosa $P_{TW}$ is equal to $P_{AW}$ when there is a small leak past the cuff.

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REFERENCES


moyennes similaires sur la paroi de la trachée, afin que l’on puisse contrôler de nombreux éléments variables que l’on croyait responsables des lésions infligées à la trachée. La compliance véritable du manchon a été mesurée avec le tube à l’intérieur et à l’extérieur de la trachée des chiens anesthésiés. On a trouvé que la pression maximale estimée transmise à la paroi de la trachée, et dérivée de ces courbes de compliance était égale à la pression de pointe du passage d’air en présence d’une légère fuite d’air passant le long de chaque manchon. Il n’y a eu que de très légères différences dans les lésions de la trachée aux différentes pressions sur la paroi trachéale entre les petits et les grands manchons de volume résiduel soumis aux essais.

**METHODE ZUM VERGLEICH ENDOTRACHEALE MANSCHETTEN**

**Kontrollierte Studie trachealer Traumata bei Hunden**

**ZUSAMMENFASSUNG**

Tracheale Verletzungen bei Hunden durch grosse und kleine Manschetten während sechsstündiger intermittender positiver Druckbelüftung wurde unter Verwendung einer speziell konstruierten Trachealröhrle verglichen. Die Manschetten waren so eingestellt, dass sie einen ähnlichen Durchschnittsdruck auf die Trachealwand ausübten, so dass viele der für die trachealen Verletzungen wahrscheinlich verantwortlichen Variablen kontrolliert wurden. Die echte Dehnbarkeit der Manschetten wurde mit der Röhre innerhalb und außerhalb der Trachea gemessen, wobei die Hunde narkotisiert waren. Der aus diesen Dehnungs-

kurven errechnete, auf die Trachealwand ausgeübte maximale Druck entsprach dem höchsten Luftwegdruck in Anwesenheit eines kleinen Lecks nach jeder Manschette. Bei verschiedenen Trachealwanddrucken gab es nur sehr geringe Unterschiede in trachealen Verletzungen durch kleine oder grosse Manschetten.

**METODO EMPLEADO PARA LA COMPARACION DE BRAZALES NEUMATICOS ENDOTRAQUEALES**

**Estudio controlado del trauma traqueal en perros**

**SUMARIO**

Se comparó el daño causado por grandes y pequeños brazales neumáticos de volumen residual durante 6 h de IPPV, utilizando un tubo endotraqueal de diseño especial. Los brazales bajo evaluación fueron ajustados para ejercer presiones medias semejantes sobre la pared traqueal, de manera tal que las muchas variantes que se cree son responsables de las lesiones traqueales fueron controladas. Se midió la elasticidad real de los brazales con el tubo dentro y fuera de la tráquea de los perros anestesiados. Se descubrió que la presión máxima estimada que se transmitía a las paredes de la tráquea, derivada de estas curvas elásticas, equivalía a la presión máxima de vía respiratoria ante la presencia de una pequeña fuga de aire por cada brazal. A diversas presiones sobre las paredes traqueales, solo se produjeron diferencias muy pequeñas en el daño traqueal entre los grandes y pequeños brazales de volumen residual que se probaron.