Direct measurement of mucosal pressures exerted by cuff and non-cuff portions of tracheal tubes with different cuff volumes and head and neck positions†

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We measured directly mucosal pressures against the cuff and non-cuff portions of the tracheal tube in different head–neck positions and tested the reliability of calculated mucosal pressures, in vivo intracuff pressures and cuff volume as determinants of directly measured mucosal pressures. We studied 10 anaesthetized, paralysed adult patients. An 8.5-mm, high volume, low pressure PVC tracheal tube was used. Microchip sensors were attached to three cuff locations (anterior, lateral and posterior) and two non-cuff locations (anterior tip and anterior aspect of the tube, 5 cm proximal to the cuff). Directly measured mucosal pressures, in vivo intracuff pressures and calculated mucosal pressures (in vivo minus in vitro intracuff pressures) were determined after brief inflation (<15 s) to 0, 5, 10 and 15 ml. In vivo intracuff pressures were then set at 30 mm Hg and the measurements repeated, first in the neutral position and then with the head–neck extended, flexed and rotated. Cuff mucosal pressures were highest anteriorly and lowest posteriorly. Non-cuff mucosal pressures did not vary with cuff volume and were approximately 15 mm Hg. Compared with the neutral position, in vivo intracuff pressures were higher in the rotated, extended and flexed positions. Compared with the neutral position, mucosal pressure increased on the anterior aspect of the tube in the flexed position by 22 mm Hg (P = 0.003), at the anterior tip in the extended position by 11 mm Hg (P = 0.002) and at the anterior tip (5 mm Hg, P = 0.05) and lateral aspect of the cuff (5 mm Hg, P = 0.03) in the rotated position. In vivo intracuff pressures and calculated mucosal pressures were moderate predictors of measured mucosal pressures; cuff volume was a poor predictor. We conclude that tracheal mucosal pressures were highest anteriorly, that non-cuff portions of the tube exerted substantial mucosal pressures and that the rotated position caused a greater increase in tracheal mucosal pressure than the extended or flexed position. Indirect methods of measuring mucosal pressure were of moderate predictive value.

Br J Anaesth 1999; 82: 708–11

Keywords: equipment, tubes tracheal; measurement techniques, mucosal pressure; complications, mucosal trauma

Accepted for publication: October 22, 1998

The pressure exerted by the tracheal tube cuff on the mucosa may exceed capillary perfusion pressure,1–3 and is a major cause of morbidity in intubated patients.4 Excessive cuff volumes and pressures are often required to form an effective seal.5 Transmitted mucosal pressures have been measured directly and indirectly in vivo, but no technique is entirely satisfactory.5 Direct measurements have been made by placing balloon-like structures between the cuff and trachea,7 8 but these balloons may distort the cuff, can be displaced by the cuff and the number of pressure points that can be investigated is limited. Indirect measurements have been made by subtracting in vitro from in vivo intracuff pressures,9 but these calculated mucosal pressures may be unreliable2 10 11 and only reflect overall pressures. Recently,
millimetre-sized strain gauge silicone microchip sensors have been developed which allow direct measurement of mucosal pressure at several locations simultaneously. In this study, we tested the hypothesis that tracheal mucosal pressures are distributed evenly across high volume, low pressure cuffs, that non-cuff portions exert no mucosal pressure, and that mucosal pressures do not vary with head and neck position. We also tested the reliability of calculated mucosal pressures, in vivo intracuff pressures and cuff volume, as determinants of directly measured mucosal pressures.

**Patients and methods**

We studied five male and five female ASA I–II adult patients in this single-site study at Cairns Base Hospital. Mean age, height and weight were 26 (range 22–41) yr, 170 (158–188) cm and 71 (50–110) kg, respectively. Ethics Committee approval and informed consent were obtained. Mucosal pressures were measured using five strain gauge silicone microchip sensors (Codman MicroSensor, Bracknell, UK) attached to the external surface of a standard size 8.5-mm internal diameter (id) tracheal tube (Hi-Lo, Mallinckrodt Medical, Athlone, Ireland) with clear adhesive dressing 45-µm thick (Tegaderm, 3M, Ontario, Canada). The sensors had a tip diameter of 1.2 mm, cable diameter 0.7 mm, cable length 100 cm, functional pressure range –50 to 250 mm Hg, temperature sensitivity less than 0.1 mm Hg °C–1, zero drift <3 mm Hg 24 h–1, frequency response 0–10 Hz and were accurate to ±2%. Attachment of the sensors and sensor cables was performed manually by placing the sensor tip in the correct position on the tracheal tube and then overlaying it with the adhesive dressing. Care was taken to ensure that the sensing element of the sensor was orientated towards the mucosal surface and aligned longitudinally with the axis of the tracheal tube. The Hi-Lo cuff has a thickness of 51 µm, cuff diameter 31.5 mm and compliance 0.252 ml cm H 2 O–1 (manufacturer’s data sheet). The sensors were attached to the following cuff and non-cuff locations on the tracheal tube (corresponding mucosal area): (1) anterior cuff (anterior proximal trachea); (2) right lateral cuff (lateral trachea); (3) posterior cuff (posterior trachea); (4) anterior tip (anterior distal trachea); and (5) anterior tube, 5 cm proximal to the cuff (laryngopharynx). All sensors were zeroed before insertion.

In vitro intracuff pressures were determined by attaching the pilot balloon to a three-way tap, a 5-ml syringe and a calibrated pressure transducer. Intracuff pressure was reduced to –40 mm Hg and the in vitro intracuff pressures measured at cuff volumes of 5, 10 and 15 ml. The orientation of the sensor was verified in vitro over the entire inflation range and zeroed in air before insertion. The measurement system was assembled with sterile components (tube–adhesive–sensors) using an aseptic technique. A standard anaesthesia procedure was followed and routine monitoring applied. Anaesthesia was induced with propofol 2.5 mg kg–1 and maintained with 1–2% sevoflurane and 100% oxygen. Nitrous oxide was avoided to minimize changes in cuff volume from gas diffusion. Neuromuscular block was produced with atracurium 0.5 mg kg–1. The uncuffed tracheal tube was inserted using a laryngoscope and the cuff (with an in vitro intracuff pressure of –40 mm Hg) was positioned in the proximal trachea, immediately distal to the vocal cords. The tube was fixed in the midline, with the tongue centralized and the radio-opaque line facing cephalad. The tracheal tube was connected to the anaesthesia breathing system using a lightweight tracheal tube mount. The head and neck were placed in the neutral position with the occiput rested on a firm indented intubating pillow, 7 cm in height. Mucosal pressures and intracuff pressures were recorded when the patient was apnoeic at cuff volumes of 0.5, 10 and 15 ml. All readings were made within 5 min of insertion of the tracheal tube. In vivo intracuff pressures were not allowed to remain greater than 30 mm Hg for more than 15 s. In vivo intracuff pressure was set at 30 mm Hg in the neutral position and the measurements repeated first in the neutral position and then (in random order) with the head and neck fully extended, fully flexed and rotated to the right. Between each positional change, the head and neck were returned to the neutral position and the in vivo intracuff pressure measured and reset at 30 mm Hg, if required. The position–orientation of the sensors were checked after removal by visual inspection. The accuracy of the probes was tested before and after use in each patient by submerging the cuff portion in water to a depth of 13.6 cm (10 mm Hg) and noting the pressure readings. Patients were followed-up 48 h after intubation.

**Statistical analysis**

Change in in vitro intracuff pressure with different head and neck positions was determined by subtracting the new value from the baseline value of 30 mm Hg in the neutral position. The change in directly measured mucosal pressure at each location with different head and neck positions was determined by subtracting the new value from the value recorded in the neutral position. Calculated mucosal pressures were determined by subtracting in vivo from in vitro intracuff pressure measurements. The distribution of data was determined using Komolgorov–Smirnov analysis. Statistical analysis was with the paired Student’s t test (normally distributed data), Friedman’s two-way analysis of variance (non-normally distributed data) and regression analysis. The relationship between mucosal pressure and other variables was determined using Pearson’s product moment correlation coefficient. The reliability of intracuff and calculated mucosal pressure in predicting mucosal pressures was analysed using the intra-class correlation coefficient (ICC). Unless otherwise stated, data are mean (range). Significance was taken as \( P<0.05 \). Statistical
Results

All tracheal tubes were inserted at the first attempt. The position–orientation of the sensors were identical and pressures were accurate before and after use. Mean mucosal pressures varied between locations and were highest against the anterior aspect of the cuff and lowest against the anterior aspect of the non-cuffed tube. All data were normally distributed. Data are mean (range) (mm Hg). *Non-normally distributed data

<table>
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<tr>
<th>Location</th>
<th>Cuff volume (ml)</th>
<th>In vivo intracuff pressure</th>
<th>In vitro intracuff pressure</th>
<th>Directly measured mucosal pressure</th>
</tr>
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<td></td>
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Table 1 Intracuff pressure (in vivo and in vitro), calculated (Cal.) mucosal pressure and directly measured mucosal pressure at five locations (two non-cuff: proximal tube and anterior tip; three cuff: anterior, lateral and posterior) with increasing cuff volume. Data are mean (range) (mm Hg). *Non-normally distributed data

Table 2 Pearson’s product moment correlation coefficient (PPCC) and intra-class correlation coefficient (ICC) for directly measured mucosal pressures at five locations (two non-cuff: proximal tube and anterior tip; three cuff: anterior, lateral and posterior) with cuff volume, in vivo intracuff pressure and calculated mucosal pressure. PPCC: +1=perfect positive correlation; 0=no correlation; -1=perfect negative correlation. ICC: \( \geq 0.75 \)=excellent reliability; 0.41–0.74=moderate reliability; \( \leq 0.40 \)=poor reliability; ns=Not significant

Table 3 In vivo intracuff and directly measured mucosal pressure changes at five locations (two non-cuff: proximal tube and anterior tip; three cuff: anterior, lateral and posterior) with flexion, extension and rotation of the head and neck from the neutral position. Statistical comparisons are compared with the neutral position. All data were normally distributed. Data are mean (range) (mm Hg). ns=Not significant

Discussion

Tracheal mucosal pressures of less than 30 mm Hg have been recommended for safe prolonged intubation.\(^ {15} \) Our data have shown that transmitted mucosal pressure commonly exceeds this value with cuff volumes of only 5 ml. This emphasizes the importance of reducing cuff volume to the minimum required to form an effective seal. We have confirmed the findings of Knowlson and Bassett\(^ {8} \) that mucosal pressures were higher in the rotated, extended and flexed positions (Table 3). The increase in intracuff pressure was greater in the rotated compared with the extended position \( (P<0.0001) \), and greater in the flexed compared with the extended position \( (P<0.0001) \). Compared with the neutral position, directly measured mucosal pressure increased at the anterior tube in the flexed position by 22 mm Hg \( (P=0.003) \), at the anterior tip in the extended position by 11 mm Hg \( (P=0.002) \), and at the anterior tip by 5 mm Hg \( (P=0.05) \) and lateral aspect of the cuff by 5 mm Hg \( (P=0.03) \) in the rotated position. Four patients had a mild sore throat at follow-up.
were not distributed evenly around the cuff and decreased gradually from the anterior to the posterior aspect of the cuff. This is because the posterior membranous tracheal wall is more distensible than the cartilaginous anterolateral wall. The high anterior tracheal wall pressure explains why cuff-related tracheal damage is most severe over the anterior trachea.16

The anterior tip and anterior tube exert substantial pressures against the tracheal and laryngopharyngeal mucosa, respectively. These pressures are unaffected by cuff volume and occasionally exceed capillary perfusion pressure. This is probably related to the preformed curve of the tube. It also suggests that inflation of the cuff does not move the tip away from the tracheal wall. We speculate that non-cuff pressures are lower with softer or S-shaped tubes and may be reduced with time as a result of thermal softening of the tube.17 It is likely that other non-cuff portions of the tube (e.g., posterior tube) exert a substantial pressure against the mucosa.18 The two non-cuff locations were chosen because trauma has been reported in the anterior laryngopharynx by cuffed tracheal tubes19 and it is known that the anterior tip is frequently in contact with the tracheal mucosa.18,20

In the flexed position, the pressure of the anterior tube against the laryngopharynx was higher than in the neutral position, but the pressure against the tracheal mucosa does not increase, despite an increase in intracuff pressure. This may be related to more even distribution of pressure over the cuff surface in the flexed position. In the extended position, the pressure against the anterior tip increased and in the rotated position the pressure at the anterior tip and lateral wall increased. Knowlson and Bassett showed that mucosal pressures on the anterior and posterior cuff were higher in the extended position.8 Our data did not support this finding. This may be related to differences in study design or type of cuff tested.

Bunegin, Albin and Smith have shown that directly measured mucosal pressure may be up to 5 mm Hg lower than in vivo intracuff pressure, depending on the cuff characteristics.2 Dobrin and Canfield11 have demonstrated mucosal pressures of as much as 15 mm Hg lower than intracuff pressures in large volume cuffs, when intracuff pressure was as high as 50 mm Hg. We have shown that intracuff pressures and calculated mucosal pressures were moderate, but not excellent predictors of cuff mucosal pressure. Calculated mucosal pressures were only marginally better predictors than intracuff pressure. This may be related to the relatively low level of elasticity of the tracheal tube tested.

A limitation of this study was that the anatomical position of the sensors was not confirmed endoscopically, a technique used by Seegobin and van Hasselt.3 They showed that mucosal pressures were highest over the tracheal rings. It is possible that some mucosal pressure changes may have been related to movement of the sensors across the tracheal rings. A potential limitation of any technique that measures pressure between two surfaces is that the sensor may generate artificially high pressures around it by distorting the surface. Our measurement system had a total thickness of 1.25 mm and the distortion effect was probably small. Our data for anterior tracheal pressures were similar to those obtained using small, flat polyethylene envelopes.8

We conclude that tracheal mucosal pressures were highest anteriorly, that non-cuff portions of the tube exerted substantial mucosal pressures and that the rotated position caused a greater increase in tracheal mucosal pressure than either the extended or flexed position. Indirect methods of measuring mucosal pressure were of moderate predictive value.

References

16 Cooper JD, Grillo HC. Experimental production and prevention of injury due to cuffed tracheal tubes. Surg Gynecol Obstet 1969; 129: 235–41