Measurement of tracheal wall pressure: a comparison of three different in vitro techniques

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Abstract

We compared three different tracheal wall pressure measuring techniques in vitro. Using a high-volume, low-pressure, cuffed tracheal tube with an internal diameter of 7.5 mm and a model trachea, the pressure difference technique, the wall pressure membrane technique and the microchip sensor probe technique with and without lubrication were studied. Wall pressures were measured after sequential injections of 0.5 ml of air into the cuff at cuff pressures ranging from 0 to 50 mmHg. The coefficient of variance was largest for the microchip sensor probe technique with lubrication (29%) and without lubrication (214%), and was lower for the wall pressure membrane technique (22%) and the pressure difference technique (19%). The wall pressure membrane and pressure difference techniques provided comparable results. The microchip sensor probe technique considerably underestimated wall pressure. These findings have an impact on the interpretation of published data on tracheal or pharyngeal wall pressure using the microchip sensor probe technique.
APPARATUS

Assessment of in-vivo and in-vitro airway wall pressure: comparison of three different approaches

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Summary

We compared three different in-vivo and in-vitro airway wall pressure measuring techniques by an in-vitro set-up. Using a high-volume low-pressure cuffed tracheal tube (internal diameter 7.5 mm) and a tracheal model the pressure difference technique, the wall pressure membrane technique and the microchip sensor probe technique with and without lubrication were studied. Wall pressures were noted every 0.5 ml air inflated into the cuff from 0 to 50 mmHg cuff pressure. Mean pressure values recorded similar volumes of air inflated and cuff pressures were compared among the three techniques. The coefficient of variance was largest for the microchip sensor probe technique without (214%) and with (29%) lubrication and lowest for the wall pressure membrane (22%) and the pressure difference (19%) technique. The wall pressure membrane and pressure difference technique provided comparable results. The microchip sensor probe technique considerably underestimated wall pressure. This has major impact on earlier published research data obtained by the microchip sensor probe technique.
Introduction

The introduction of newer artificial airways such as supra-glottic airway devices and modern high-volume low-pressure cuffs has led to several publications evaluating and/or comparing wall pressure at different sites of the human airway [1-16]. Measurement of pharyngeal and tracheal wall pressure exerted by artificial airways and their cuffs is of great interest, because of pressure-induced reduction of mucosal perfusion and related morbidity [17-19]. However, the impaired mucosal perfusion as well as the increased tracheal wall pressure is very difficult to assess directly. Therefore, validated research tools to closely estimate these parameters are of great importance. In literature, mainly three different techniques to assess tracheal wall pressure in-vitro and in-vivo have been used: pressure difference techniques [20, 21], wall pressure membrane techniques [22, 23] and microchip sensor probes [1-16, 24-26]. So far, only limited data about reliability or comparability of these different techniques has been published [2, 8, 9]. The aim of this study was to compare three different currently used wall pressure measuring techniques by an in-vitro set-up.
Methods

We investigated the following in-vivo and in-vitro wall pressure measuring techniques, as described in literature previously:

**Pressure difference technique**

A well accepted pressure difference technique was described by Mackenzie et al [20]. In summary, it states that the pressure $WP_{\text{difference}}$ on a tracheal wall can be estimated by the formula

$$WP_{\text{difference}} = P_{\text{inserted}} - P_{\text{uninserted}}$$

where $P_{\text{uninserted}}$ is the intra-cuff pressure measured after inflating a certain amount of air of a freely suspended tracheal tube cuff. The same tracheal tube is then inserted into a tracheal model and the cuff inflated with the same amount of air that resulted in $P_{\text{inserted}}$. This technique is suitable for in-vivo [2, 9, 27] as well for in-vitro research designs [20].

**Wall pressure membrane technique**

The wall pressure membrane technique as described 1981 by Tonnesen et al [23] consists of a tracheal model with a hole covered by a membrane at the internal wall and an electronic transducer connected to the outer hole. The tracheal tube cuff is placed to cover the hole. This approach is only applicable for in-vitro research designs [22, 23, 28].

**Microchip sensor probe technique**

A miniature intra-cerebral pressure sensor probe (Codman, Raynham, MA, USA) is placed between the tracheal or pharyngeal wall and the cuff [1-16, 24-26]. To not alter cuff compliance, we taped the sensor probe to the tracheal wall so that the pressure sensor opening faces against the tracheal tube cuff. This technique has been used for in-vivo [2, 8-12, 14-16], in post-mortem studies [1, 4-7, 13] as well as in-vitro studies [3].
**Experiments performed**

Using an in-vitro experimental tracheal model, SIMS Portex Profile Soft Seal cuffed tracheal tubes (SIMS Portex, Hythe, Kent, UK) with internal diameters (ID) of 7.5 mm and an residual outer cuff diameter (OCD) of 30 mm at 20 cmH₂O were investigated. Following complete deflation of the cuffs and equilibration of cuff pressure to atmospheric pressure, the pilot balloons of the tracheal tube cuffs were connected to a low-compliant 50ml syringe (Codan Medical, ApS, Rodby, DK) using a three-way stopcock and a 0.5 m stiff infusion line extension (PE-infusion line, Clinico Medico GmbH, Bad Mersfeld, Germany). The 50 ml syringe was placed in an Asena™ infusion pump (Alaris® Medical Systems, Hampshire, UK). An invasive pressure transducer (Baxter, Ad Uden, NL) attached to an anaesthesia monitor (AS5; Datex, Helsinki, Finland) was connected to the side port of the three-way stopcock for cuff pressure measurement. For all experiments below, the tube cuffs were inflated by the 50ml Codan syringe at a speed rate of 150 ml/h up to a cuff pressure not higher than 50 mmHg in order to avoid distortion of the tracheal tube cuff. Cuff pressures resulted at each incrementally inflated 0.5 ml aliquots of air as displayed by the infusion pump were noted.

**Assessment of pressure difference technique (WP\textsubscript{difference}) and the wall pressure membrane technique (WP\textsubscript{membrane})**

The intra-cuff pressures were assessed with the tracheal tube cuff before (P\textsubscript{uninserted}) and after insertion into the tracheal model (P\textsubscript{inserted}) made from polyvinyl chloride (PVC) (ID 20 mm) with integrated wall membrane pressure transducer assembly faced to the centre of the tube cuff (Figure 1). Herewith, WP\textsubscript{difference} was calculated and WP\textsubscript{membrane} was simultaneously assessed with the wall membrane pressure transducer placed below, above or 90° lateral of the tracheal tube cuff to exclude any position effects.
Assessment of pressure difference technique ($WP_{\text{difference}}$) and the microchip sensor probe technique ($WP_{\text{microprobe}}$)

Again, the intra-cuff pressures were assessed with the tracheal tube cuff before ($P_{\text{uninserted}}$) and after insertion into the tracheal model ($P_{\text{inserted}}$) with calculation of $WP_{\text{difference}}$. This time, a microchip sensor probe (Figure 2: Codman intracranial pressure probe, Raynham, MA) was attached to the tracheal tube cuff inserted in the tracheal model. The sensor was placed facing the centre of the tube cuff. $WP_{\text{microprobe}}$ was measured with the microchip sensor probe placed below, above or 90° lateral of the tracheal tube cuff to exclude any position effects.

In a second step, $WP_{\text{microprobe}}$ was assessed again with the microchip sensor probe fully covered by lubricant jelly (Aquasonic 100, Parker Laboratoires, Inc., Fairfield, NJ) to assure appropriate pressure transmission.

All measuring equipment (pressure transducer, wall pressure sensor, microchip pressure sensor) was calibrated and confirmed for accuracy within or attached to the artificial trachea using different level of inspiration pressure (0-40 mmHg) provided by an anaesthesia respirator (ADU; Datex, Helsinki, Finland). All experiments were performed twice with the same four cuffed tubes (8 measurements per experiment) at 20° C room temperature and ambient pressure. One tracheal model with membrane pressure transducer and two different microprobe sensor probes were used for the study. To exclude alteration in cuff compliance by prior cuff inflations, unchanged cuff compliance was confirmed prior to each series of experiments.

Statistical analysis

Data are presented as mean (SD). The coefficient of variance (CV) in percent was used to mathematically describe pressure variations (standard deviation (SD) / mean x 100). Volumes of air inflated and cuff pressures were plotted against wall pressures. Wall pressures ($WP_{\text{membrane}}$ and $WP_{\text{microprobe}}$) measured at different rotational positions of the artificial trachea were compared using unpaired, two-sided T-test ($p<0.05$).
Results

Cuff volume - wall pressure curves are shown for all techniques investigated in Figure 3. The mean (SD), range and coefficient of variance of calculated and measured wall pressures are expressed in Table 1. The main finding was that the not lubricated microchip sensor probe technique does not reflect wall pressure at all, whereas the lubricated microchip sensor probe technique slightly underestimated wall pressures when compared to the two other techniques. Median CV was largest (214%) for WP_{microprobe \ not-lubricated}, 29 % for WP_{microprobe \ lubricated}, 22 % for WP_{membrane} and lowest (19 %) for WP_{difference}. Neither for the wall pressure membrane technique nor for the microchip sensor probe technique a statistically significant difference was found between different sensor placements.

Cuff - wall pressure curves are demonstrated in Figure 4. As appropriate for a high-volume low-pressure cuff the resulted WP_{membrane} and WP_{difference} were similar to P_{inserted}. Again WP_{microprobe \ lubricated} was slightly lower than P_{inserted}. 


Discussion

In this study we compared three different wall pressure measuring techniques as to their reliability in evaluating new airway devices.

The main findings were that the pressure difference technique and the wall pressure membrane technique seem to reliably reflect wall pressure whereas the Codman microchip sensor probe technique without lubrication at the sensor probe resulted in entirely unreliable wall pressure estimations. To date, the most popular way to assess wall pressure involves the use of a miniature intra-cranial microchip sensor probe (Codman, Raynham, MA, USA) placed between the tracheal wall and the tracheal cuff. Recent studies with this device included in-vitro set-ups [3], studies with anaesthetized and paralyzed patients [2, 6, 8-12, 14-16] as well as post-mortem examinations [1, 4, 6]. From a practical point of view, there are several advantages related to the use of this device. Firstly, it is a commercially available equipment tool and therefore delivers easily reproducible results if used by different researchers. Secondly, it can be easily attached to all kinds of airway devices with simple tapes. Since it is very small, the same airway device can be simultaneously examined in this manner at different wall sites. Yet, we found an important disadvantage of this pressure sensing device if used outside its designated purpose, namely intracerebral pressure monitoring. Its deep sensor level causes false low or even absent pressure reading because pressure transmission from the cuff unto the sensor cannot take place. Even worse, the same phenomenon happens if the sensor surface is rotated away from the cuff or from the airway mucosa respectively. Consequently, in-vivo measurements of airway wall pressure using the Codman microsensor mounted on an airway device will considerably underestimate wall pressure. Furthermore large variation in pressure values will result, depending if mucus, secretion or mucosal folds will transmit pressure from the airway wall the sensor of not. These large variations are found in many to the investigations on wall pressure measurements using the Codman microchip sensor probe. [7, 15],

Although lubrication with commonly used jelly can partly help overcome this drawback constant lubrication of the sensor when inserted into the airway cavity is questionable as stable rotational position
will be. We fear that previous reports on wall pressure assessed with codman microchip sensor probes must be critically reviewed whether lubrication nor post-confirmation of sensor position has been performed [7, 15].

Based on our finding, the wall pressure difference technique allowed to reliably assessing wall pressure. This simple approach to wall pressure estimation is based on an in-vitro-study [21] reported more than 30 years ago. It states that the tracheal wall pressure should correspond to \( P_{tw} = P_{ic} - P_{f(d)} \), where \( P_{ic} \) is the intra-cuff pressure and \( P_{f(d)} \) is a function of the cuff diameter (d) and the stiffness of the cuff material(s).

Consequently, if the intra-cuff pressure is monitored, the tracheal wall pressure will always be less to that value or almost equal if \( P_{f(d)} \) is very low. The great advantage of this in-vivo and in-vitro approach is that no sensing devices are necessary. Wall pressure can be calculated based on the readily measurable intra-cuff pressure before and after insertion of the airway device. Recently, Young and colleagues [27] used this technique to adjust wall pressure at 30 cm H2O in a low-volume high-pressure cuff tracheal tube. The main problem with in-vivo application of the wall pressure difference technique is that the human trachea is neither circular nor stiff. In the non-circular C-shaped trachea different wall pressures will result at different sites but not measured by the wall pressure difference technique and of course, as a theoretical assumption, no real pressure values can be found.

The wall pressure membrane technique is an exclusively in-vitro method and was used as a reference technique in our study. Yet if a properly designed and constructed setting is guaranteed, cuff-induced lateral wall pressures by new airway devices can be accurately tested in a reproducible way. Several authors in earlier reports describe this method [22, 23, 28]. Tonnesen et al [23] described a D-shaped tracheal model with an elastic posterior wall and a firm anterior wall with a 6-mm diameter hole where a latex rubber tubing was cemented to the concave surface of the split cylinder. An electronic pressure transducer connected to the hole measured lateral wall pressure. A separate transducer attached to the cuff inflation valve measured cuff pressure. They found that wall pressure tended to be low (<35 Torr) and cuff pressure closely approximated wall pressure when a seal was achieved with a volume of air in the cuff less than cuff residual volume. These authors stated that their tracheal models are delivering reproducible
testing of various tracheal cuffs. They noted though that these models can never accurately imitate a human trachea and therefore only estimate the relationship between these measurements and tracheal mucosal pressures.

One limitation of our study is its in-vitro design with a rigid tracheal model and taping the sensor at the tracheal model wall and not at the cuff. A round model tracheal with wall side placement of the sensors was chosen in order to create uniform study conditions.

We did not include wall pressure measurements with transducers lying between the wall and the cuff as reported in several studies [24-26]. These in-vitro studies involved flat balloons, rubber bladders or flat polyethylene envelopes as pressure sensing devices. However, these transducers are prone to misreading as large transducer devices distort the cuff and thus the cuff pressure and are not sensitive to small pressure differences. Small transducers on the other side both limit the range of recordable pressures and small air leaks result in gross errors. Aware of these disadvantages, we did not consider such a measurement technique in our study.

In conclusion, among the three commonly used different wall pressure measuring techniques, the wall pressure membrane technique and the pressure difference technique provided comparable results. Yet the most often used technique involving a miniature intra-cerebral Codman microchip sensor probe between the wall and the cuff considerably underestimates wall pressure due to recessed pressure sensor at the probe head. This has serious impacts on the validity and interpretation of results from earlier published research data [1-16] obtained by the Codman microchip sensor probe technique.
References


### Table 1: Wall pressures exerted by tracheal tube cuffs measured at each incrementally inflated 0.5 ml aliquots of air with the cuff restricted in a tracheal model using three different assessment techniques. (CV = coefficient of variance; WP = wall pressure)

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<th>Range</th>
<th>CV</th>
<th>WP&lt;sub&gt;difference&lt;/sub&gt; (mmHg) Mean±SD</th>
<th>Range</th>
<th>CV</th>
<th>WP&lt;sub&gt;microprobe not lubricated&lt;/sub&gt; (mmHg) Mean±SD</th>
<th>Range</th>
<th>CV</th>
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Legends of the Figures 1-4

**Figure 1**
Tracheal model (internal diameter: 25 mm) made from stiff PVC with a hole (ID 5 mm) covered by an elastic membrane at the internal wall. The tracheal tube cuff is placed to cover the hole. Pressure exerted to the membrane is transmitted by water within a short, stiff tube to the electronic pressure transducer.

**Figure 2**
Photograph of a miniature intra-cerebral pressure sensor probe (Codman, Raynham, MA, USA). The picture clearly demonstrates that the sensor is placed below the level of the probe surface.

**Figure 3**
Volumes of air inflated by the infusion pump (x-axis) are plotted against wall pressures measured with each of the three techniques investigated (y-axis). Values are presented as mean.

**Figure 4**
Cuff pressures measured (x-axis) are plotted against wall pressures measured with each of the four techniques investigated (y-axis). Values are presented as mean.
Figure 3

The graph shows the relationship between the volume of air inflated (in ml) and the wall pressure in mmHg for different conditions:
- WP Membrane
- WP Difference
- WP Microprobe not lubricated
- WP Microprobe lubricated

The graph illustrates how the wall pressure increases with the volume of air inflated, with different curves for each condition.
Figure 4

- WP Membrane
- WP Difference
- WP Microprobe not lubricated
- WP Microprobe lubricated

Cuff pressure [mmHg] vs. Wall pressure [mmHg]