TEMPERATURE, HUMIDITY AND MUCUS FLOW IN THE INTUBATED TRACHEA

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SUMMARY

Mucus flow rates were measured in the intact trachea of anaesthetized dogs, using a radioactive tracer technique. Measurements were made before intubation, and after intubation at inspired air temperatures of 32, 37 and 42°C, with a constant inspired water vapour content of 33 mg/l; and again at each temperature with a relative humidity of 75%. No significant difference in mucus flow rate was found under any of these conditions.

In an investigation of the effect on tracheal mucus flow rate of varying the relative humidity of inspired air, at a constant temperature of 37°C, it was found that an inspired humidity of at least 50%, and preferably 75% was required to maintain mucus flow (Forbes, 1973). A relative humidity of 75%, at 37°C, represents a water content of inspired air of 33 mg/l. It was decided to investigate the effect on mucus flow rate of changing the inspired air temperature whilst maintaining an inspired air-water content of 33 mg/l, and to observe the effect of changing the inspired air temperature with a constant relative humidity of 75%. This should reveal the effect of temperature on mucus flow, and whether mucus flow is dependent on absolute or relative humidity of inspired air within the temperature range studied. Air temperatures of 42, 37, and 32°C were chosen; the last representing the lowest temperature which will support a water content of 33 mg/l without the addition of water droplets.

MATERIAL AND METHOD

Twelve greyhounds, weighing 25–35 kg, were anaesthetized with intravenous thiopentone 30 mg/kg, or pentobarbitone 20–25 mg/kg, followed by 120-mg increments of pentobarbitone for maintenance. Each dog was placed in the left lateral position on a warming blanket, with the trachea horizontal, and a rectal thermometer and an arterial catheter were inserted. Mucus flow rate was measured with a radioactive marker using the method of Baetjer and Bates (1966), as modified by Marin and Morrow (1969). A single scintillation counter, fitted with a collimator in which there were two apertures, was positioned over the neck, so that both apertures were transverse to the long axis of the trachea (fig. 1). The trachea was exposed by incision and blunt dissection caudal to the apertures, and 10 μCi of 99mTc as pertechnetate ion, in 10 μl of saline, was injected through a fine 25-gauge needle, into the tracheal lumen. As the pertechnetate travelled in the mucus stream under each aperture, the count rate was recorded on a constant speed chart recorder. Thus a count rate peak occurred under each aperture in turn (fig. 2). The time interval between peaks represented the time taken for the pertechnetate to cover the distance in the trachea between the apertures. This distance was previously determined to be 6.6 cm for a point source of 99mTc, 4 cm below the collimator face. If the assumptions are made that the pertechnetate in saline is bound to the mucus in such a way that its rate of movement is a constant reflection of that of the mucus (Marin and Morrow, 1969), and that any change in mucus flow produced by the injection of 10 μl of solution is in a constant ratio to the flow before intervention, then comparative mucus flow rates can be calculated.

After induction of anaesthesia, three measurements of mucus flow were made. A straight metal tube, 30 cm in length, 1 mm wall thickness, and 12 mm internal diameter, was then passed into the trachea and its tip was positioned just below the vocal cords. The tube was connected to a T-circuit, which was supplied with a high flow of air, the temperature and relative humidity of which was varied by adjusting relative flows through a hot water bath humidifier (Forbes, 1973) and a hot dry air blower (fig. 3). Before each measurement of
Fig. 1. Sodium iodide crystal and collimator construction for detection of pertechnetate in tracheal mucus.
(a) End view of base, positioned so that the apertures are at right angles to the long axis of the trachea.
(b) Cross section A-A.

Fig. 2. Count rate of pertechnetate bound to mucus in the trachea of a greyhound, as it travels under each aperture of the collimator assembly in turn. The arrow marks the point of insertion of pertechnetate.
mucus flow, the temperature and relative humidity of the inspired gas was measured at the T-piece, with a wet and dry bulb psychrometer whose mercury thermometers were calibrated in 0.1°C increments and checked with a British Standard thermometer. This gives a relative humidity value with an accuracy of 1%. The expiratory limb of the T-piece was extended to ensure no dilution of the inspired gas with room air. The dog breathed spontaneously at 8–12 b.p.m. and periodic manual hyperinflation was performed to prevent atelectasis. Arterial oxygen and carbon dioxide tensions and pH were measured in the 1st, 3rd and 5th hours after induction of anaesthesia. Measurements of mucus flow, at a relative humidity of 75% and at an absolute humidity of 33 mg/l., were made at each inspired air temperature of 32, 37, and 42°C. As 75% relative humidity represents, at 37°C, an absolute humidity of 33 mg/l., the measurements were made under five different conditions. The accepted limits of inspired air humidity are shown in table I. The order of the inspired temperatures and humidities was randomized. Ten minutes after commencing exposure to each inspired air temperature and humidity, three measurements of mucus flow were made at approximately 10-minute intervals. In 7 of the 12 dogs a further three measurements were made at 10-minute intervals, at the end of the experiment, when the endotracheal tube had been removed, and the dog had been breathing room air for 10 minutes.

To avoid altering the conditions of temperature and humidity under observation and to avoid stimulating mucus secretion, intratracheal temperature was not measured in these dogs. However, peak inspired and expired air temperatures at 1 cm beyond the endotracheal tube tip were measured in another dog, using a rapid response thermocouple*, inserted into the lumen of the endotracheal tube (table II). These results are considered in the Discussion.

**RESULTS**

The mean values for inspired air temperature, measured at the T-piece before each pertechnetate insertion were as follows: 32°C, 32.0 (SD=0.2°C); 37°C, 37.1 (SD=0.2°C); 42°C, 42.0 (SD=0.3°C).

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**TABLE I. Limits of humidity of inspired air at 32, 37 and 42°C, in intubated anaesthetized greyhounds, at which measurements of intracheal mucus flow rates were made.**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Absolute humidity (mg/l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>96-100</td>
<td>32.5-33.8</td>
</tr>
<tr>
<td>37</td>
<td>73-76</td>
<td>32.0-33.4</td>
</tr>
<tr>
<td>42</td>
<td>57-59</td>
<td>32.2-33.3</td>
</tr>
</tbody>
</table>

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**FIG. 3. Apparatus used to provide a high flow of air, at different measured temperatures and relative humidities, across a T-piece.**

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Rectal inspired air temperatures were 32, 37 and 42°C and the humidity was either 75% or 33 mg/l., at each temperature. Each value represents the mean of three measurements.

Arterial blood-gas values (table III) were maintained within the physiological range. The mean values of three measurements of mucus flow at each inspired air temperature and relative humidity are shown in table IV. No significant difference was found between mucous flow rate in the unintubated trachea at the beginning and end of the experiment, or between values before and after endotracheal intubation. No significant difference was found between mucous flow rates at inspired air temperatures of 32, 37, and 42°C, either when relative humidity was 75%, or when absolute humidity was maintained constant at 33 mg/l. In all cases, P was >0.05. Statistical analyses were performed by means of the Analysis of Variance.

**DISCUSSION**

Mucus transport in the trachea depends on the strength and frequency of the ciliary beat, and on the volume, viscosity, and relative thickness of mucus layers (Yeager, 1971). The mucus secretory apparatus is more sensitive than the ciliary mechanism to changes in temperature and humidity, ciliary beat being known to continue when mucus flow has ceased (Dalhamm, 1956). Thus the earliest changes in mucociliary function should be those of mucus secretion reflected in a change in mucus flow rate.

In this study the factors known to affect mucus flow rate, apart from temperature and humidity, were controlled as far as possible. Mechanical stimulation, which leads to an outpouring of mucus (Rylander, 1966), was kept to a minimum by using small drops of perctehnetate and by the use of a fine needle passed between the cartilagenous rings of the tracheal wall. As there is conflicting evidence as to whether change in inspired oxygen concentrations may reduce mucus flow (Laurenzi, Yins and Guarneri, 1968; Marin and Morrow, 1969), the inspired oxygen concentration was maintained at 21%, and the arterial oxygen tensions were constant over the period of study. Although a lightening of anaesthesia occurred, manifested by a progressive fall in arterial carbon dioxide tensions, the lack of a difference in mucus flow rate between intubated values at the beginning and end of the experiment would support the contention of Marin and Morrow (1969), that the depth of barbiturate anaesthesia does not influence mucus flow.

The effect of a lack of humidity on mucus flow is well established; mucus thickens and flow slows...
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... to a halt. Cilia continue to beat for a short time, but stop eventually (Dalhamm, 1956; Kilburn, 1967). Various authors have reported this phenomenon occurring at different temperatures and levels of humidity. In the excised trachea of the rabbit, Tore-malm (1961) demonstrated that alternating flow of air at 21°C, 50% saturated and containing 9 mg H₂O vapour/l., in one direction, and fully saturated air at 37°C in the other direction, caused ciliary activity to stop within 30 min. Asmundsson and Kilburn (1970) observed that drying of resected dog lungs at room temperature caused mucus flow to stop and ciliary beat to cease. Dalhamm (1956) found that introducing room air at 50% relative humidity directly into the tracheas of anaesthetized rats caused the ciliary beat to cease within 10 min. Thus, in vitro and in vivo, air which is 50% saturated at room temperature stops mucus flow and ciliary beat. In previous studies on anaesthetized dogs breathing through an endotracheal tube the author found that inspired air at 37°C and 50% relative humidity, containing 22 mg H₂O vapour/l., stopped mucus flow in 5 dogs out of 7, but no such effect was seen with air at 37°C and 75% relative humidity, containing 33 mg H₂O vapour/l. (Forbes, 1973). This agrees with the clinical finding of Sara (1965) that the inhalation of room air through a tracheostomy, although giving inspiratory conditions of 26.5–28°C, 83% relative humidity and a water vapour content of 22 mg/l., fails to prevent drying and inspissation of mucus. In the present study, the lowest water vapour content of inspired air (75% relative humidity at 32°C) was 25 mg/l.

It is difficult to separate the effects of inspired air temperature and mucosal temperature on mucus flow rate. Baetjer (1967), studying chicks breathing spontaneously through either the mouth or the nose, found that increasing the inspired air temperature from 5 to 35°C increased tracheal mucus flow, but he ascribed this to the concomitant increase in mucosal temperatures. However, Dalhamm (1956) studying the exposed tracheas of rats found no correlation between inspired air temperatures in the range 31–41°C and mucus flow rate, provided rectal temperature remained constant. The present findings of a constant mucus flow rate, between 32°C and 42°C, at a constant absolute humidity would tend to support this. Dalhamm found also that increasing the rectal temperature from 37 to 39°C increased flow, but that a further increase to 42°C reduced flow. Hill (1928) made similar observations in the resected trachea of the horse. As increasing the metabolic rate with 1-thyroxine did not increase mucus flow rate (Baetjer, 1967), it is assumed that the body temperature effect is a direct effect of the temperature of the mucosa. Dalhamm (1956) has demonstrated that the reduction of flow rate at the higher temperatures was not a fatigue effect. Thus it would seem that mucus flow in the trachea is influenced by mucosal temperature rather than air temperature per se. Body temperature was maintained constant in the present study.

The finding of a constant mucus flow rate at inspired air temperatures of 32, 37, and 42°C, both at a constant humidity of 33 mg H₂O vapour/l., and at a constant relative humidity of 75% could be explained on the following basis. During nasal respiration the inspired air at the top of the trachea, at a temperature of 32–34°C, is usually in excess of 90% saturated, containing 34 mg H₂O vapour/l. (Ingelstedt, 1956; Sara, 1965). As inspired air passes down the trachea and upper airways, it is heated to body temperature by a process of “turbulent convection” and full saturation occurs by evaporation of water from the mucosal surface (Walker, Wells and Merrill, 1961). In the dog, alveolar air is fully saturated at 38°C and contains 46 mg H₂O vapour/l. (Dery et al., 1967). The mucosa, meanwhile, is cooled by the loss of latent heat of evaporation during inspiration, and warmed and wetted by condensation from saturated air during expiration.

During inspiration, the heat loss from the mucosa required to raise the temperature of the air is small in comparison with that resulting from evaporation of water (Walker, Wells and Merrill, 1961). Furthermore the ability of the endotracheal tube to exchange heat and water (Dery et al., 1967) would buffer the temperature of the air entering the trachea. Thus, as shown in table II, the temperature range to which the tracheal mucosa was exposed was not 32–42°C, but 34.2–39.4°C. Hence the major factor affecting mucosal temperature during inspiration would be the degree of evaporative cooling, which depends on the water content of inspired air.

Under the conditions of this study the water content of the inspired air varied from 25 to 42 mg/l. As this was always less than the 46 mg/l. occurring in alveolar air, evaporative cooling of the mucosa during inspiration could occur. Exposure of the trachea to a higher water content of inspired air at above body temperature could be expected to result in condensation of water with release of latent heat, and heat gain by the mucosa (Walker, Wells and Merrill, 1961), leading to the rise in mucus...
flow rate reported by Dalhamm (1956) and Hill (1928) at higher mucosal temperatures. When the water content of inspired air was 25 mg/l, evaporation of a small quantity of water from the endotracheal tube would raise it to the 27 mg/l found in the trachea during normal inspiration through the mouth (Ingelstedt, 1956). Exposure to a lower water content of inspired air would be expected to lead to excessive cooling and drying of the mucosa with a fall in mucus flow rate (Forbes, 1973).

Caution should be exercised in applying these results to the clinical situation. Although it has been shown that mucus flow in the trachea is maintained, between inspired air temperatures of 32 and 42°C at 75% relative humidity, it is emphasized that all exposures were of short duration (40 min), that the water content of the inspired air, even at 42°C, was below that of saturated air at body temperature, and that the temperature of alveolar air in the human is 37°C normally, compared with the dog temperature of 38°C. It would seem prudent to maintain the inspired air at temperatures between 32 and 37°C, with a water vapour content of 33 mg/l.

ACKNOWLEDGMENTS

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REFERENCES


TEMPERATURE, HUMIDITY ET ECOCULEMENT MUQUEUX AU NIVEAU DE LA TRACHEE INTUBEE

SUMMARY

Les taux d'écoulement du mucus ont été mesurés au niveau de la trachée intacte de chiens anesthésiés, en recourant à une technique de marquage radioactif. Ces mesures ont été effectuées avant et après intubation, à partir de l'air inhalé, à des températures de 32°C, 37°C et 42°C avec une teneur constante de vapeur d'eau inhaleé de 33 mg/l et une nouvelle fois aux différentes températures précitées pour une humidité relative de 75%. Aucune différence significative n'a été enregistrée en ce qui concerne les taux d'écoulement du mucus dans les conditions décrites plus haut.

TEMPERATUR, FEUCHTIGKEIT UND SCHLEIMFLUSSEN IN DER INTUBIERTEN TRACHEA

ZUSAMMENFASSUNG


TEMPERATURA, HUMECTACION Y SECRECION DE MOCO EN LA TRAQUEA INTUBADA

RESUMEN

Se midieron las tasas de secreción de moco en la tráquea intacta de perros anestesiados, usando una técnica de marcador radioactivo. Las mediciones se efectuaron antes de la intubación y después de la misma, con temperaturas del aire inspirado de 32°C, 37°C y 42°C, manteniendo constante el vapor de agua inspirado a 33 mg y además para cada temperatura con una humedad relativa de 75%. No se apreció una diferencia significativa respecto a la tasa de secreción de moco en cualquiera de estas condiciones.