TRACHEAL MODELS WHICH SIMULATE THE COMPLIANCE OF THE ADULT MALE TRACHEA

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SUMMARY

Earlier models of the human trachea have not taken the characteristic compliance of the trachea into account. Two tracheal models are presented, which simulate the compliance of the adult male human trachea, intended for more valid laboratory testing of the function of the cuffs of tracheal tubes. The two models simulate the conditions with and without controlled ventilation.

KEY WORDS


The tracheal models used previously for testing the performance of high- and low-residual volume cuffs and for investigating the diffusion of nitrous oxide and oxygen into cuffs of tracheal tubes have been either non-compliant or of very small compliance. However, the normal human trachea is a compliant structure, with approximately 60% increase in cross-sectional area when inflated to 6 kPa.

Different materials such as glass, PVC and Perspex have been used in laboratory experiments as models of the trachea [1-3]. The National Catheter Co. has manufactured a trachea model, Imatrach [4] which accurately reproduces the size and shape of an adult human trachea, but still has a small compliance, increasing its cross-sectional area only by less than 5% at a 6 kPa pressure. It is manufactured from soft PVC, and is used for testing cuffs in a Draft American Standard for Tracheal Tubes.

The aim of the present investigation was to devise tracheal models with compliance close to that of the normal human trachea.

MATERIALS AND METHODS

Thin, elastic sheets of latex, 70 and 160 µm thick, and polyurethane 25, 50 and 100 µm thick (PT 6300 S from Deerfield Urethane Inc., South Deerfield, MA, U.S.A.) (measured with Mitutoyo calipers) were used to make thin-walled, elastic tubes ("stockings") of varying diameter. By trial and error, different stockings were combined to obtain pressure-volume characteristics as close as possible to those published for the isolated human trachea [5, 6] (fig. 1). Adhesives which did not interfere with the elasticity of the models were used. For joining the polyurethane sheets, polyurethane dissolved in a tetrahydrofuran–cyclohexanone solution (1:1) was used, and a commercial rubber solution was used to join the rubber sheets. The diameter of the stockings was critical, as less than 0.5 mm deviation was found to change the curve markedly. The inside diameter of the tracheal models was chosen to be 20 mm, corresponding to the diameter of the average adult male trachea [7, 8]. The models were 12 cm long and kept in place by a rack.

Moreno and colleagues [6] used CT scans to show that the pressure-area relationship of the trachea, measured in vivo, is different from that of the isolated trachea. This relationship was measured during Valsalva manoeuvres—that is, under conditions similar to those obtained during artificial ventilation (fig. 1). Consequently, it was necessary to devise two different tracheal models: one simulating conditions during spontaneous ventilation with the

![Pressure-volume curve](https://example.com/pressure-volume.png)

**Fig. 1.** Pressure-volume curve (○) of the adult human trachea and volume increase of the trachea caused by stretching (●) [5], together with the total volume increase minus volume increase caused by stretching (□). *Regression line calculated from the results published by Moreno and colleagues [6]: r = 0.8921.*

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TRACHEA MODELS

TRACHEAL MODEL

VOLUME

FIG. 2. Apparatus for measuring the pressure-volume relationship of tracheal models. The water-filled models were submerged in a water-filled container and exposed to transmural pressures from 0 kPa to 6 kPa.

Fig. 3. Pressure-volume curves for two identical examples for each of the two model tracheas, compared with the Inmatrach model trachea (■). Model trachea A (○ and ●): latex 70 μm, 20 mm diameter and polyurethane 100 μm, 25 mm diameter. Model trachea B (▼ and ▲): latex 160 μm, 20 mm diameter and polyurethane 25 μm, 25 mm diameter. Mean (SD) from five measurements.

RESULTS

It was found that models simulating the isolated trachea required an inner stocking of 70-μm latex, 20 mm in diameter, and an outside stocking of 100-μm polyurethane, 25 mm in diameter; those simulating the conditions during artificial ventilation required an inner stocking of 160-μm latex, 20 mm in diameter, and an outside stocking of 25-μm polyurethane, 25 mm in diameter. The outside stockings required small openings to the atmosphere.

The pressure–volume curves are shown in figure 3. The reproducibility of results from two identical models was good (fig. 3).

DISCUSSION

Tracheal models are necessary for testing the function of high and low residual volume cuffs of tracheal tubes in a standard manner. The most important difference between high and low residual volume cuffs is seen when large inflation pressures are needed. Even in these cases, the cuffs must give an airtight seal during inflation whilst not exerting undue pressure on the tracheal mucosa during expiration. Cuffs with too small a resting diameter cannot possess both attributes [1]. If a non-compliant tracheal model is used for testing, erroneous results are obtained, because dilatation of the trachea is not taken into account.

Croteau and Cook [5] measured volume–pressure and length–tension relationships in isolated human tracheas. As the trachea models presented here had a constant length, the volume increase caused by stretching was subtracted from the total volume increase (fig. 1) and the resulting curve was considered to be the optimal for a model of the isolated trachea (model A in figure 3). In practice, it was not possible to reproduce exactly the ascending part of the curve, as this would imply a latex membrane around 30–35 μm in thickness, and this would have too small a mechanical strength. Moreno and colleagues [6] found a different volume–area relationship for the trachea in vivo using Valsalva manoeuvres (during pressure conditions similar to those of controlled ventilation). They used CT scans for measuring cross-sectional area and an oesophageal balloon for measuring transmural pressure difference. The regression line calculated from their results is shown on figure 1 (r = 0.8921). They concluded that, during inflation, part of the intra-thoracic pressure is transmitted to the cervical tissue around the trachea, and this modifies the dilatation of the trachea. As a result, dilatation of the trachea, as the pressure increases, follows a relatively straight line from 0 kPa to 6 kPa. The trachea model B in figure 3 has been adapted to simulate the curves published by Moreno’s group [6]. Tracheal model A, accordingly, is proposed for testing the pressure increase in cuffs caused by diffusion of nitrous oxide and oxygen, without the influence of controlled ventilation, while model B is proposed for testing cuff function during artificial ventilation.

The two stockings in the models work together. An increase in pressure inside the model dilates the trachea dilated by the cuff only, and one simulating conditions during artificial ventilation, with the trachea dilated by the ventilator pressure.

The pressure–volume relationship of the models was measured using the method of Martin and Proctor [9]—the water-filled model was submerged into a water-filled glass container (fig. 2). The volume increase of the model was measured at differential pressures over the wall of the models from 1 kPa to 6 kPa. Each series of measurements were repeated five times. Two models of each type were measured, to show if the construction of the models was reproducible.
inner stocking until it reaches the outside stocking. This leads to a sharp increase in compliance for model A, and modifies the compliance of model B to reproduce a straight line.

The tracheal models have several shortcomings. The tracheal cartilages and their associated tissues have different mechanical characteristics. At present, it is probably not possible to produce models which take into account these differences and reproduce tracheal hysteresis [10, 11]. The trachea may also have different shapes, as shown by Mackenzie and colleagues [12], and this diversity is not accounted for by the models demonstrated here. Nevertheless, the two models described, which simulate the compliance of the normal adult male trachea, are an improvement on earlier models.

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REFERENCES