

## Endotracheal Tube Cuff Residual Volume and Lateral Wall Pressure in a Model Trachea

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The authors constructed a D-shaped tracheal model with an elastic posterior wall, thus stimulating normal tracheal anatomy more closely than previous models. The performance of 9-10 tracheal tube cuffs, of 2-3 different tube sizes (7.0-10.0 mm, ID), from six different manufacturers were tested in the model. Cuff residual volumes ranged from 1.78 to 27.35 ml. Cuff pressure and lateral wall pressures exerted by the cuff on the model were measured at the time a seal was achieved which just prevented leakage of water past the cuff. When a seal was achieved with a volume of air in the cuff less than cuff residual volume, wall pressure tended to be low (<35 torr) and cuff pressure closely approximated wall pressure. There was no relationship between cuff compliance and wall pressure. There were large differences between brands in the wall pressures required to effect a seal in the model. The authors conclude that intratracheal tubes should have cuffs with large residual volumes. This would permit some latitude in tube size selection while ensuring that a seal could be achieved before the cuff is inflated to its residual volume. (Key words: Airway: tracheal model. Complications: tracheal stenosis. Equipment: cuffs, endotracheal. Lung: trachea.)

EXCESSIVE MUCOSAL PRESSURE from inflatable endotracheal and tracheostomy tube cuffs can cause ischemic tracheal damage. Therefore, the lateral wall pressure exerted by the cuff should be kept below tracheal mucosal capillary pressure (25-35 torr).<sup>1</sup> Many currently marketed tubes have cuffs designated as "high-volume," "high-compliance," "low-pressure" cuffs. We have observed major differences in intracuff pressure between different brands of such tubes during clinical use. In this study, we have constructed a tracheal model for measuring lateral wall pressure; measured cuff residual volumes and compliances of different tube sizes from different manufacturers; and correlated the wall pressure required to prevent a water leak in our model with cuff residual volume and intracuff pressure.

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### Materials and Methods

We constructed a tracheal model with a firm anterior wall and an elastic posterior wall to simulate tracheal anatomy (fig. 1). A plastic cylinder (2.9 cm diameter, 10 cm length) was split lengthwise and a 6-mm diameter hole was drilled through the anterior wall. Latex rubber tubing (2.8 cm diameter, 10 cm length)§ was cemented to the concave surface of the split cylinder. This formed a D-shaped tracheal model with an elastic posterior wall. Lateral wall pressure was measured by an electronic transducer connected to the hole in the anterior wall by a short segment of fluid filled tubing. A separate transducer attached to the cuff inflation valve measured cuff pressure (CP).

### RESIDUAL VOLUME AND CUFF COMPLIANCE

Each cuff was inflated once until palpably tense and checked for air leaks. The cuff was deflated and reexpanded with small increments of air, until cuff pressure rose linearly to a pressure above 15 torr. A cuff volume versus cuff pressure graph was constructed and visually extrapolated to zero pressure for determination of residual volume (RV) (fig. 2). Specific cuff compliance ( $C_{\text{cuff}}$ ) was calculated from the slope of the extrapolated line divided by residual volume ( $C_{\text{cuff}} = \Delta \text{volume} \cdot \Delta \text{CP}^{-1} \cdot \text{RV}^{-1}$ ). Dividing compliance by RV converts  $\Delta \text{volume}$  to a fractional change in volume per unit change in pressure. This corrects for the fact that, for example, adding 1 ml of air to a cuff with a volume of 2 ml represents a 50 per cent change as opposed to a 5 per cent change for a cuff with an RV of 20 ml.

### SEALING VOLUME AND WALL PRESSURE

The endotracheal tube was then positioned in the model so that the midportion of its cuff would overlie the hole in the anterior wall. The cuff was inflated with 1-ml increments of air until water poured into the top of the model failed to leak past the cuff (sealing volume,

§ Penrose drain.

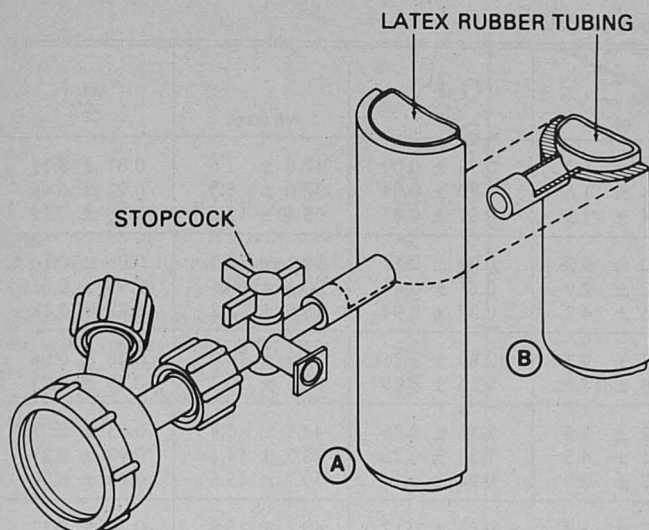


FIG. 1. Schematic drawing of tracheal model. (A) Representation of assembled model. The tube between the stopcock and model was filled with water using a needle and syringe to carefully exclude any air bubbles. An electronic transducer (not shown) was attached to the dome. (B) A cutaway view showing rubber tubing covering the pressure sensing hole in the anterior wall.

SV). Wall pressure (WP) and cuff pressure were recorded at sealing volume.

Data from at least nine tubes each, of 6 brands and 2 or 3 sizes were evaluated. Regressions expressing the WP/CP ratio and WP as functions of the SV/RV ratio were calculated from standard formulae.

## Results

Table 1 summarizes the data (mean  $\pm$  SD) for each tube brand and size. For tubes with SV/RV  $\geq 1.0$ , the wall pressure producing a watertight seal correlated with

the ratio of sealing volume to the residual volume ( $r = 0.96$ ,  $WP = 3.5 \cdot (SV/RV) + 31.5$ ;  $P < 0.005$ ) (fig. 3). The logarithm of the WP/CP ratio was inversely proportional to the logarithm of the SV/RV ratio ( $r = 0.92$ ;  $\log WP/CP = -0.51 \times \log (SV/RV) + 0.8$ ) (fig. 4). Of 156 tubes with an SV/RV ratio  $< 1.0$ , 37.2 per cent achieved a watertight seal at pressures  $\leq 35$  torr compared to 7.1 per cent of those with SV/RV ratios  $\geq 1.0$  ( $P < 0.001$ ).

There were major differences in cuff residual volume between brands and a tendency for cuff volume to increase with tube size. Tubes C and F appeared to have higher specific compliances than the remainder of the brands, but analysis of variance did not reveal a statistically significant difference. There was no correlation between specific cuff compliance and lateral wall pressure required to affect a seal.

Brands "A" and "B" produced minimal posterior displacement of the posterior wall of the model compared to other brands.

## Discussion

We feel that this tracheal model overcomes several problems with previous models. First, its shape conforms to the more common C-shape or D-shape of human tracheas, which are uncommonly cylindrical.<sup>2,3</sup> Secondly, the posterior wall is elastic. Thirdly, there are no intrusions into the "tracheal" lumen which can cause artifactual pressure recordings.

Disadvantages of the model include a lack of transparency, difficulty in bonding rubber to plastic, lack of temperature control, and our failure to achieve a system (due to bonding problems) allowing "ventilation" of an artificial lung.

FIG. 2. Example of the graphic extrapolation method for determination of residual volume. The slope of the extrapolated line was calculated and then divided by the cuff residual volume to determine specific compliance.

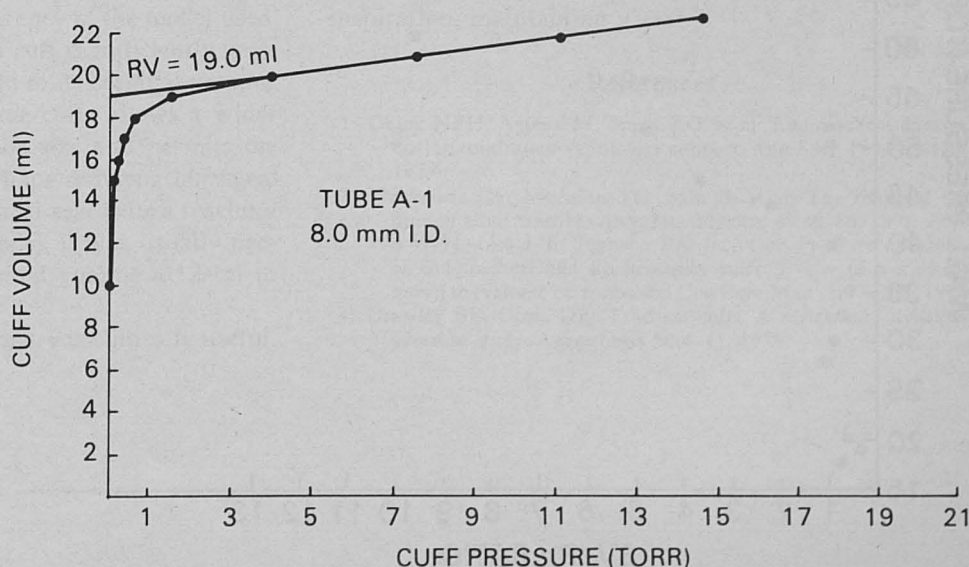


TABLE 1. Summary of Data

Tube Brand	ID (mm)	N	SV (ml)	RV (ml)	C <sub>cuff</sub> (μl·torr <sup>-1</sup> ·ml <sup>-1</sup> )	SV/RV	WP (torr)	WP/CP
A	7.0	10	9.7 ± 0.82	12.51 ± 0.91	16 ± 5.2	0.78 ± 0.09	17.6 ± 7.6	0.81 ± 0.11
	8.0	9	13.7 ± 0.87	19.4 ± 0.57	14 ± 1.6	0.70 ± 0.04	32.6 ± 5.3	0.92 ± 0.06
	9.0	10	12.9 ± 1.91	22.46 ± 1.05	14 ± 1.5	0.57 ± 0.07	35.4 ± 12.5	0.98 ± 0.11
B	7.0	10	11.0 ± 0.82	12.41 ± 0.88	20 ± 6.2	0.89 ± 0.12	30.1 ± 10.1	0.93 ± 0.10
	8.0	10	10.8 ± 1.23	17.69 ± 0.99	22 ± 2.9	0.61 ± 0.06	20.1 ± 5.4	0.95 ± 0.07
	9.0	10	10.2 ± 0.92	27.35 ± 0.89	16 ± 4.2	0.37 ± 0.04	18.3 ± 7.2	0.88 ± 0.18
C	8.0	10	21.8 ± 1.87	1.78 ± 0.36	37 ± 9.3	12.80 ± 3.26	75.9 ± 10.0	0.28 ± 0.06
	9.0	10	16.3 ± 1.49	1.91 ± 0.55	38 ± 17.6	9.56 ± 4.25	63.3 ± 10.7	0.35 ± 0.06
D	7.0	10	10.5 ± 0.85	4.97 ± 0.67	22 ± 5.5	2.15 ± 0.36	44.1 ± 6.4	0.63 ± 0.06
	8.0	10	9.3 ± 1.49	7.62 ± 0.9	21 ± 4.5	1.24 ± 0.26	28.3 ± 14.1	0.92 ± 0.22
	9.0	10	10.5 ± 1.72	11.17 ± 0.42	17 ± 2.9	0.94 ± 0.14	39.7 ± 15.5	0.95 ± 0.06
E	7.0	9	7.78 ± 0.97	9.22 ± 0.81	12 ± 1.8	0.85 ± 0.12	40.2 ± 15.8	0.70 ± 0.12
	8.0	10	7.3 ± 0.95	7.72 ± 1.27	14 ± 6.8	0.97 ± 0.24	52.3 ± 8.8	0.84 ± 0.06
	9.0	10	7.5 ± 0.71	7.89 ± 0.97	16 ± 4.9	0.96 ± 0.12	50.7 ± 11.5	0.77 ± 0.12
F	8.0	9	11.89 ± 1.36	2.58 ± 0.58	31 ± 7.6	4.88 ± 1.59	51.8 ± 13.9	0.37 ± 0.06
	10.0	9	10.33 ± 0.87	2.81 ± 0.45	31 ± 5.0	3.77 ± 0.67	46.6 ± 15.8	0.37 ± 0.14

All values are mean ± SD; ID = Internal Diameter; A = American Hi-Lo; B = Argyle "Soft-One"; C = Dynacor; D = Portex "Soft Seal";

E = Lanz (pressure relief valve removed from cuff); F = Shiley Tracheostomy Tube.

The extrapolation method for determining residual volume proved to be easy and reproducible. We could not reliably determine residual volume by filling a cuff to a "just-inflated" state determined visually, nor by locating the point on the volume axis at which cuff pressure began to rise.

There was no apparent relationship between cuff compliance and wall pressure at the sealing point. In fact, cuffs with the highest compliance were associated with the highest wall pressures. Compliances varied from 16–22 μl·torr<sup>-1</sup>·ml<sup>-1</sup>, except for tubes C and F which had higher values. This may have been caused by the effects

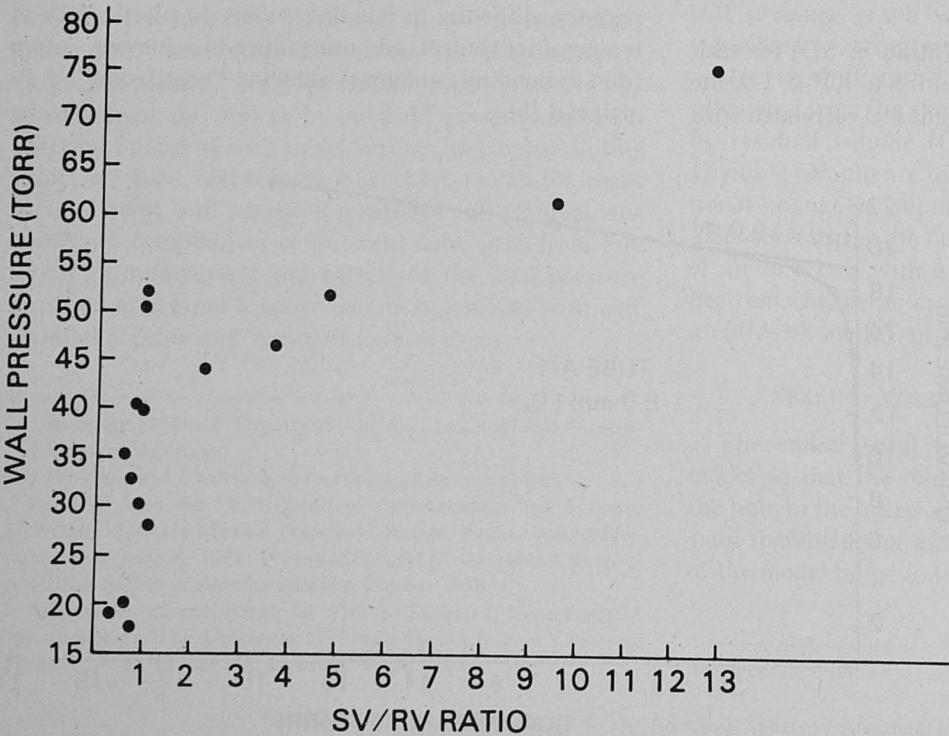


FIG. 3. Relationship between SV/RV ratio and wall pressure at which a watertight seal was effected. Each point represents the mean value of nine or ten tubes for each brand and size (see table 1).

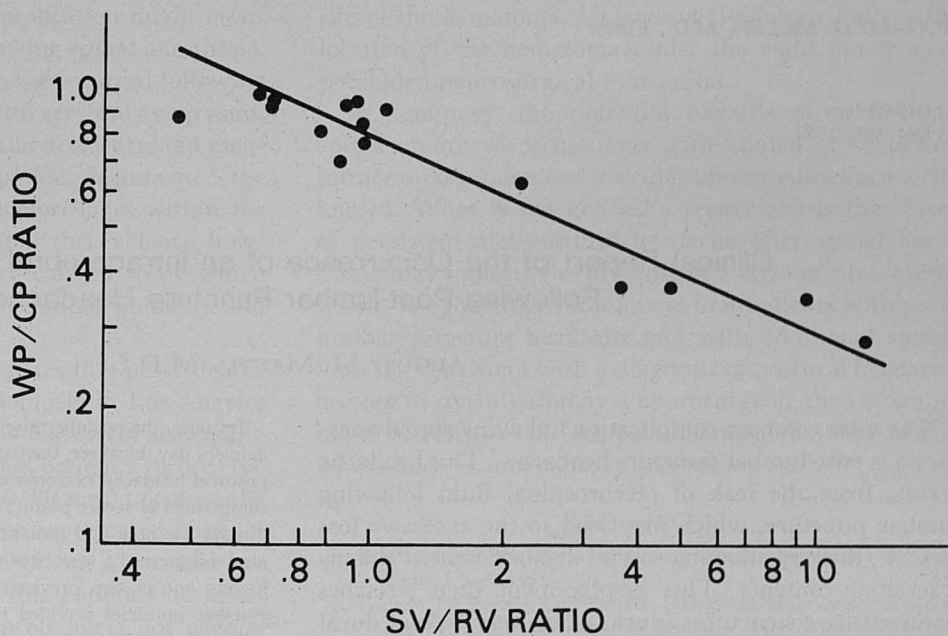


FIG. 4. Relationship (Log vs. Log) between the SV/RV ratio and WP/CP ratio illustrating that the lower the SV/RV ratio, the more closely the cuff pressure represents the wall pressure. Each point represents the mean value of nine or ten tubes of each brand and size (see table 1).

of their extremely low residual volumes on the calculations rather than real differences in compliance, although the nature of the plastics in their cuffs was different from the remainder of the tubes. Hence, we believe that specific cuff compliance is not an important determinant of tracheal wall pressure for the tubes studied.

It is clear that the SV/RV ratio was a major determinant of ultimate wall pressure, especially if the ratio was greater than unity. When this ratio was less than 1.0, wall pressure varied widely and with no apparent relationship to any of the parameters measured. We agree with the impression<sup>3</sup> that some of the large residual volume cuffs formed a series of wrinkles which had to be compressed before a seal was achieved. This often required high wall pressures. Precise observations were prevented by the lack of transparency of the model used.

We conclude that the optimal cuff is sufficiently large to effect a seal before being filled to its residual volume. The use of large residual volume cuffs allows a wider margin of error in selecting tube size and permits the selection of a smaller tube, perhaps reducing laryngeal damage, while achieving a tracheal seal before reaching residual volume. In this size model, it was usually necessary to use cuffs with a residual volume > 12 ml to achieve a seal at low WP.

The measurement of cuff pressure is clinically useful,

in that cuff pressure always exceeded wall pressure. If the cuff pressure is measured routinely and maintained at a level below 20–25 torr, one can be sure that wall pressure will be below the theoretical capillary pressure in the tracheal mucosa. When the SV/RV ratio is less than unity, wall pressure and cuff pressure will closely approximate one another. Cuff pressure and wall pressure differences became progressively larger as the residual volume of the cuffs became smaller. Despite this, the ultimate wall pressure at the point of sealing was always higher with small volume than large volume cuffs. Although we could not investigate the effect of positive pressure ventilation on the wall pressure in the current model, we would predict that lower pressure would cause a seal for ventilation because cuff pressure rises during inspiration, maintaining a seal.<sup>4</sup>

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