Distal projection of insufflated gas during tracheal gas insufflation

CHRISTOPHER S. CARTER, JOHN R. HOTCHKISS, ALEXANDER B. ADAMS, MARY K. STONE, AND JOHN J. MARINI

Regions Hospital, St. Paul 55101; and University of Minnesota, Minneapolis, Minnesota 55455

Received 20 February 2001; accepted in final form 14 December 2001

Distal projection of insufflated gas during tracheal gas insufflation. J Appl Physiol 92: 1843–1850, 2002; 10.1152/japplphysiol.00160.2001.—Tracheal gas insufflation (TGI) flushes expired gas from the ventilator circuitry and central airways, augmenting CO₂ clearance. Whereas a significant portion of this washout effect may occur distal to the injection orifice, the penetration and mixing behavior of TGI gas has not been studied experimentally. We examined the behavior of 100% oxygen TGI injected at set flow rates of 1–20 l/min into a simulated trachea consisting of a smooth-walled, 14-mm-diameter tube. Models incorporating a separate coaxial TGI injector, a rough-walled trachea, and a bifurcated trachea were also studied. One-hundred percent nitrogen, representing expiratory flow, and 100% oxygen, representing TGI gas, were also studied. One-hundred percent oxygen, representing expiratory flow, passed in the direction opposite to TGI at set flow rates of 1–25 l/min. Oxygen concentration within the “trachea” was mapped as a function of axial and radial position. Three consistent findings were observed: 1) mixing of expiratory and TGI gases occurred close to the TGI orifice; 2) the oxygenated domain extended several centimeters beyond the endotracheal tube, even at high-expiratory flows, but had a defined distal limit; and 3) more distally from the site of gas injection, the TGI gas tended to propagate along the tracheal wall, rather than as a central projection. We conclude that forward-directed TGI penetrates a substantial distance into the central airways, extending the compartment susceptible to CO₂ washout.

TGI enhances CO₂ elimination from intubated, mechanically ventilated patients (5, 8, 16). Fresh gas instilled into the trachea displaces exhaled CO₂-laden gas from the anatomic and mechanical dead space, thereby reducing CO₂ rebreathing (6, 7, 13, 15). The flushed compartment includes the rebreathed volume in the ventilator circuit [from the circuit wye through the endotracheal tube (ETT)] and the dead space of the patient’s trachea proximal to the TGI injector orifice. 1 When injection is forward directed (toward the carina), the flushed volume potentially includes central airways distal to the injector orifice.

Despite numerous laboratory and clinical investigations, there remain fundamental uncertainties regarding the behavior of the TGI gas jet in the trachea. These include the extent of distal penetration of TGI gas and, consequently, the contribution of distal washout to CO₂ elimination.

Conventional TGI increases end-expiratory lung volume, inducing a dynamic hyperinflation similar to auto-positive end-expiratory pressure (PEEP) (1, 11, 15), Giacomini et al. (4), Cereda et al. (3), and Imanaka et al. (6, 7) have explored the use of reversed-flow (mouthward) TGI, which eliminates TGI-induced auto-PEEP, even augmenting expiratory flow through a Venturi effect, and possibly reduces other adverse effects of conventional TGI. If the distal penetration of conventional TGI is minimal, efficacy of such a reverse-tip TGI catheter should be comparable to conventional TGI, with the washout effect occurring mainly in the ventilator circuitry in either case. Indeed, Cereda et al. (3) found no difference in efficacy between conventional and reversed-flow TGI in sheep. Similarly, Imanaka et al. (7) found that, whereas there was a trend toward increased efficacy of conventional over reversed-flow TGI in sheep, the difference was insignificant.

The magnitude of distal washout may well depend on geometry and flow velocities. Two studies from our laboratory (10, 11), comparing forward- and reversed-flow TGI, suggest that the contribution of distal washout (beyond the ETT tip) may account for as much as 25% of the total TGI benefit under certain physiological conditions. Similarly, Cavanagh and Eckmann (2), using a finite-element mathematical model of gas jets, determined that the TGI gas should be expected to propagate a significant distance as a central jet, with gas exiting back along the perimeter of the airway. That model may not represent clinical conditions, however, as it did not include expiratory flow opposing TGI. The mathematical model also assumed unimpeded expiratory flow through an open annulus, rather than through a resistive ETT, with the trachea otherwise occluded by the tube cuff. The present study uses a

1 “Proximal” here is in the direction of the mouth; “distal” refers to the direction of the peripheral airways.

Address for reprint requests and other correspondence: A. B. Adams and C. S. Carter, Regions Hospital, 640 Jackson St., St. Paul, MN 55101 (E-mail: alex.b.adams@healthpartners.com).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
physical model to measure the penetration and mixing behavior of TGI in the setting of expiratory flow with an ETT present.

METHODS

The experimental apparatus is illustrated in Fig. 1. A smooth-walled plastic tube, 56 cm in total length, with a 14-mm inside diameter, was used as a tracheal analog. The proximal end of the “trachea” was intubated with a 7.0 ETT (7 mm ID, 10 mm OD) containing a 2-mm ID channel integrated in the wall, the orifice of which is 0.5 cm proximal to the ETT tip (Hi-Lo ETT; Mallinkrodt, St. Louis, MO). A seal was effected by inflating the cuff. Expiratory gas flow (“bias flow”) was simulated by passing dry 100% nitrogen through the tube, flowing constantly toward the proximal end at rates of 1, 2.5, 5, 10, and 25 l/min.

The Reynolds numbers calculated for these bias flows fell within the range (<2,300) expected to produce laminar flow conditions within the lumen, except for the highest flow, 25 l/min, which produced a borderline turbulent Reynolds number of 2,525 (14). TGI was simulated by introducing a continuous flow of dry 100% oxygen gas into the tracheal tube via the integral channel of the ETT at rates of 1, 2.5, 5, 10, and 20 l/min. Both expiratory and TGI flows were set with a flowmeter (Timeter Instrument, Lancaster, PA).

As the above model differs in several aspects from real airway anatomy, three variations of the original model were constructed to determine the effect of specific geometric features on TGI gas behavior. These modifications are illustrated in Fig. 2. Each model retained the ETT with inflated cuff, so as to maintain an “end-plate” effect in the airway, but delivered TGI through a separate, straight 2-mm-ID metal “injector” tube, which passed through the ETT. The injector was centered and aligned coaxially with the tracheal tube, with its orifice even with the ETT tip. This straight injector removed the oblique exit angle of the TGI gas from the Hi-Lo channel orifice, reducing the potential for irregularities in the ETT plastic molding to deform the TGI gas flow profile. Maximum TGI flow with the straight injector was limited to 10 l/min because of increased resistance within the long injector tube.

A “straight-injector” model incorporated this new injector within the same tracheal tube as the original model.

A “corrugated wall” model addressed the concern that the human trachea, not being smooth walled, may impart significant turbulence to expiratory flow, affecting the flow dynamics within the system.

In this model, the straight TGI injector was centered within a length of corrugated straight-ventilator tubing of 20–25 mm ID, with the corrugation depth being 2.5 mm. Two flow combinations were tested with this model variant: 1 l/min TGI with 10 l/min bias and 10 l/min TGI with 2.5 l/min bias.

Finally, a “bifurcated” model used the straight injector within a smooth, 14-mm-diameter tracheal tube but placed a symmetric 60° bifurcation into two identical 14-mm “bronchial” tubes 5 cm distal to the injector orifice. In three separate experiments, bias flow was passed through these bronchial tubes with both equal and unequal flow rates: 1 l/min TGI with 10 l/min bias (5 l/min from each “bronchial” limb), 10 l/min TGI with 5 l/min bias (2.5 l/min from each limb), and 10 l/min TGI with 7.5 l/min bias (5 and 2.5 l/min from the bronchial limbs).

At each tested combination of bias flow and TGI flow, the TGI gas profile was mapped as a function of distance from the ETT tip and radial position within the tracheal tube. At 1-cm intervals, a hollow 22-gauge steel needle (0.4 mm ID, 0.7 mm OD) was introduced through the tracheal tube wall perpendicular to the tube’s long axis. At each distance, samples were obtained from the needle orifice at 0-, 2-, 4-, 6-, 8-, 10-, 12-, and 14-mm depths. Distance was increased until oxygen was no longer detected in the lumen. In the Hi-Lo ETT model, the ETT was positioned such that the TGI orifice (which is eccentric, embedded in the ETT wall) was at 4-mm depth. The plane of symmetry of the ETT was aligned with the path of the sampling needle (see Fig. 1). Mixed gas was aspirated through the sampling needle from one site at a time, at a constant rate of 0.3 l/min, by using a metered pump. This gas was then passed to a sensitive oxygen analyzer (limited diffusion, solid zirconium oxide fuel cell type; model S-3A1, Radiometer).

2 The Reynolds number (Re) is a dimensionless quantity given by $Re = \frac{dV\mu}{\rho}$, where $\mu$ is the kinematic viscosity of the gas, $-0.15$ cm$^2$/s in this case (14), $d$ is the tube diameter, and $V$ is the average gas velocity in the lumen.

Fig. 1. Schematic of the experimental apparatus with use of the Hi-Lo endotracheal tube (ETT). A cross section shows the alignment of the ETT with the sampling probe. TGI, tracheal gas insufflation.

Fig. 2. The straight-injector and straight-tube (A), corrugated wall (B), and bifurcated (C) experimental models.
Ametek, Pittsburgh, PA). When stable analyzer readings were observed, the measured oxygen concentration ([O2]) was recorded with a precision of 0.1%. This allowed a two-dimensional map of TGI gas concentration ([O2]) within the “trachea” to be constructed for each combination of bias flow and TGI flow rate.

To quantify the therapeutic TGI effect for each flow combination, we calculated the volume of expiratory gas displaced by TGI from the tracheal lumen as follows. The probe spacing can be used to divide the volume into subsections within the trachea into concentric semicircular regions, as shown in Fig. 3. The volume of such a region is

\[ \text{Volume} (\text{mm}^3) = \text{cross-sectional area} (\text{mm}^2) \times \text{length (mm)} \]

where \( r \) is the radial distance of the sample from the tube’s cross-sectional center (in mm).

The sample volume must be multiplied by the proportion of expiratory gas in the volume that has been displaced by TGI. As TGI is the sole source of oxygen in the system, this is equal to the measured percent oxygen, [O2].

The total volume of expiratory gas displaced from the dead space distal to the ETT tip is then the sum over all measurements

\[ \text{Volume} = \sum \left( \frac{\pi r^2 - \pi (r - 2)^2}{2} \times \text{length} \right) \]

Note that this washout volume includes only the region distal to the ETT tip. Additional washout occurs in the mechanical dead space proximal to the ETT tip, as well, but its magnitude is variable, depending on the circuit volume contained between the ETT tip and the wye. It is, therefore, not included in the washout volume calculation. It can be considered to be proportional to [O2] in the well-mixed gas of the proximal trachea.

RESULTS

Figure 4 maps TGI gas concentration for varying TGI and bias-flow rates in the Hi-Lo tube model. Three qualitative observations can be made regarding the distribution of injected TGI gas. First, there was essentially no discrete jet of TGI gas detected for the majority of flow combinations. Extensive mixing of TGI and bias gas occurred in close proximity to the ETT tip, particularly at lower bias flows and high-TGI flows. Furthermore, this area of mixed gas extended several centimeters beyond the ETT, in many cases, occupying approximately one-half of the tube length that contained detectable TGI gas, with relatively little reduction in TGI gas concentration. Second, although the gas in the proximal trachea just beyond the ETT tip was extensively mixed and nearly homogeneous, the [O2] was observed to be slightly higher on the side opposite the TGI injector orifice. Third, in the more distal trachea, the TGI gas did not propagate as a central projection; in fact, it tended to propagate peripherally, along the tube wall.

Figure 5 shows the maximum penetration distance of detectable oxygen from the ETT tip as a function of TGI and bias flows.

The washout volume data are shown in Fig. 6. Note that TGI and bias-flow rates exerted effects of opposite direction but similar magnitude on TGI penetration distance and washout volume, independent of the flow combination.

Gas concentration maps that use the straight-injector model, with gas flow rates identical to those in Fig. 4, are shown in Fig. 7. The straight-injector model reduced the asymmetry present in the TGI gas concentrations compared with the Hi-Lo tube model, supporting the assertion that much of this asymmetry was due to angulation of the TGI gas exiting the Hi-Lo tube orifice. Although the straight injector did not produce an enhanced central area of high-TGI gas concentration consistent with a central “jet” of TGI gas, extensive mixing of the TGI and expiratory gases still occurred and predominated throughout the zone of detectable TGI gas. The jet effect was most prominent when TGI flow was low, particularly \( \leq 2.5 \text{ l/min} \). Despite enhanced jet formation, the TGI penetration distances and washout volumes (Figs. 5 and 6) were not increased relative to those achieved with the Hi-Lo tube, except for TGI flows of \( \approx 2.5 \text{ l/min} \).

A gas concentration map that uses the corrugated wall model is shown in Fig. 8. Penetration distances and washout volumes were greater with the use of the corrugated wall model than the smooth wall model.

Gas concentration maps that used the bifurcated model are shown in Fig. 9. TGI gas penetration distances and washout volumes were greater than in the nonbifurcated model and did not appear to be greatly affected by asymmetric bias flow in the two limbs. It was observed (not shown) that angular deviations of the TGI injector of 20° toward one limb of the bifurcation had a similar minor effect on the relative penetration distances along the two limbs.
DISCUSSION

These results suggest that, under most tested conditions, TGI gas extends a substantial distance distally from its injection site. CO₂ removal from the tracheal dead space appeared to be mediated primarily through mixing and dilution, rather than displacement. The presence of an organized projection, as predicted by Cavanagh and Eckmann (2), which might produce bulk displacement of dead-space gas, was limited to conditions of low-TGI and high-bias flows unlikely to be encountered clinically. From a clinical standpoint, conditions of low-bias flow that mimic late expiration are of primary interest because the washout effect of TGI appears to be concentrated in this time period (15). The relative ineffectiveness of TGI in early expiration may be explained by the strong, inverse relationship of washout volume with bias flow that we observed in the present study.

If one examines the penetration distance at TGI and bias-flow rates that mimic conditions near end-expiration, for example, TGI of 10 l/min and expiratory bias flow of 2.5 l/min, it is apparent that, despite the absence of a formed gas jet, TGI gas penetration into the central airways is significant. In this model, which

Fig. 4. TGI gas profiles in the Hi-Lo model. Left: bias flow is constant at 5 l/min, whereas TGI is varied from 1 to 10 l/min. Right: TGI is constant at 10 l/min, whereas bias flow is varied from 1 to 25 l/min. Note the lack of a central projection at the orifice and the tendency for TGI to be directed toward the (lower) wall opposite the orifice and to propagate along the tube walls.

Fig. 5. Maximum detectable TGI gas penetration distances in centimeters. Solid symbols and lines represent the Hi-Lo tube model; dotted lines represent the straight-injector/straight-tube model. Injector geometry does not consistently affect penetration distance, although, at very low-TGI flows, the straight injector tends to project farther. Note the similar response of penetration to independent changes in TGI and bias flows. Corrug, corrugated; Bifurc, bifurcated.
approximates human tracheal dimensions, penetration under the above conditions is ~13 cm, suggesting that the TGI gas envelope extends throughout the trachea. Extension into the main and even the lobar bronchi is also possible, although these areas were not accurately modeled in this study. This represents a mechanism that could account for our laboratory’s previous findings, that up to 25% of the CO₂ washout effect of TGI occurs distal to the ETT tip (11). It also explains the result of another study by our group (12) showing that catheter advancement beyond a position 10 cm above the carina did not significantly increase efficacy; our results suggest that the majority of the central airways may be flushed from this position. Alterations of model geometry, the presence of a bifurcation, nonsmooth walls, and angled TGI flow, do not significantly alter these results. This is also consistent with our laboratory’s earlier finding that TGI efficacy did not vary with different catheter configurations (12). It is arguable that reversing the direction of TGI might reduce the distal penetration and thus reduce washout volume. Comparisons of forward- and reverse-flow TGI in animal models have yielded variable results (7, 11, 12); the effect of reverse-flow TGI in this model is a subject for further study.

Fig. 6. Washout volumes. Solid symbols and thick lines represent the basic Hi-Lo ETT model; thin lines represent the straight-injector/straight-tube model. Injector geometry has minimal effect on washout volume. Note the similar response of washout to independent changes in TGI and bias flows.

Fig. 7. TGI gas profiles in the straight-injector/straight-tube model. Left: bias flow is constant at 5 l/min, whereas TGI is varied from 1 to 10 l/min. Right: TGI is constant at 10 l/min, whereas bias flow is varied from 1 to 25 l/min. Although no TGI ‘jet’ is seen, a diffuse central projection appears at low-TGI flows.
The early and nearly complete mixing of the TGI gas in the trachea was unexpected and inconsistent with the theoretical description published by Cavanagh and Eckmann (2). We believe that, as TGI undergoes an abrupt change in luminal diameter at its ori- firce, it develops a strongly turbulent character, which promotes rapid mixing throughout the tracheal tube (14). The presence of strong turbulence is supported by significant temporal fluctuations of measured [O₂] observed at middle distances in the mixed-gas zone. In addition, the substitution of a cuffed ETT for the open, nonresistive out- fl ow of the Cavanagh and Eckmann (2) model may have played an important role in disrupting laminar flow within the lumen.

The higher concentration of TGI gas opposite the Hi-Lo tube ori- firce was apparently due to the gas stream being directed obliquely, rather than along the tracheal tube axis, by the ETT. The straight injector did not display this behavior. Our results suggest that such oblique flow does not affect TGI gas propagation, and the Hi-Lo ETT appeared to be as effective a con- duit for TGI as the straight injector.

The tendency of the TGI gas to propagate along the tracheal tube wall was also surprising. It had been assumed that the TGI gas would extend as a central projection. We suspect that, at all but very low-TGI flows, turbulence in the TGI disrupted any central projection. This contention is supported by the observation of a more distinct central “jet” of high-TGI gas concentration produced by the more regular ori- firce of the straight injector. At low-TGI flow rates, attenuating turbulent behavior, this central projection became more distinct. Turbulent TGI gas would be expected to have a nearly constant axial velocity throughout the tube cross section. The bias-flow gas, on the other hand, should be more laminar and, as such, will exhibit axial velocity, which is greatest in the tube center and slowest close to the tube walls. As these two opposing wavefronts collide, the TGI gas will meet the most opposition at the tube center and the least opposition peripherally, especially at high rates of bias flow. In contrast, bias flow in the corrugated tube model should have been more turbulent, with its velocity varying less along the tube diameter. As seen in Fig. 8, the corrugated tube model did produce a straighter TGI-bias gas interface.

The present study has several limitations relating to the physical model used. Whereas its overall dimen- sions are representative of the human trachea, the surface contours and bifurcation geometry are only rough approximations. Additionally, expiratory flow in vivo emanates from a series of converging bifurcations, rather than a straight tube, and thus experiences changes in velocity and degree of turbulence as it moves mouthward. Although the expiratory gas in our model may differ from physiological expiratory gas in its degree of turbulence and velocity profile, substantial geometric alterations in the model, such as corru- gated walls and addition of a bifurcation, designed to impart turbulence and deceleration to the expiratory gas, did not substantially alter results. Therefore, we believe that, taken together, our models constitute a reasonable analog of flow in the trachea.

Fig. 8. TGI gas profile in the corrugated wall model (A) compared with the straight-injector/straight-tube model (B) at 10 l/min TGI and 2.5 l/min bias. Gas profiles are similar, but, in the corrugated model, TGI penetrates slightly farther and TGI propagation along the tube walls is less pronounced.

Fig. 9. TGI gas profiles in the bifur- cated model. TGI of 10 l/min is opposed by symmetric bias flow of 2.5 l/min for each limb (A), and asymmetric bias flow of 2.5 l/min for upper limb and 5 l/min for lower limb (B). When bias flow is symmetric, TGI projects along each limb nearly equally; asymmetric bias flows produce mildly asymmetric TGI projection.
It must be noted that our physical model describes the equilibrium condition as constant TGI flow opposes constant expiratory flow. Such a model may not fully describe the behavior of gases in the central airways during tidal ventilation, when expiratory flow is variable. We observe, however, that, whereas varying expiratory flow affects the magnitude of TGI penetration, it has little effect on the pattern of TGI gas distribution within the tracheal lumen. Therefore, the gas distribution pattern is similar over the range of expiratory flows tested. Indeed, during tidal ventilation, the region of TGI gas may simply grow and shrink in a continuous fashion as expiratory flow changes. If this is true, the instantaneous TGI gas distribution should conform to the profiles presented here at equivalent expiratory flow rates. Because the equilibrium gas profiles tended to establish themselves quickly, the authors believe that a substantial proportion of clinical ventilator strategies would allow such equilibrium or near-equilibrium conditions to occur during the critical late-expiratory period. However, the use of very short expiratory periods or brief TGI injections, which do not allow sufficient time for equilibrium conditions to develop, may produce significantly different gas patterns. The disposition of TGI gas under such non-steady-state conditions is difficult to predict based on the present model.

Despite its small gauge and low sampling flow, the measurement probe utilized in this model could potentially distort the gas profile inside the tracheal lumen. Such distortion could result either from the physical presence of the probe itself or from the flow of gas being drawn into the probe orifice. Regarding the potential for turbulence generated by the probe itself, several observations suggest that any such effect was of minor importance. First, such distortion would be expected to be greater when the probe was fully inserted than when the needle projected only a short distance, or not at all, into the lumen. In the three models that use a straight injector, no such gas profile asymmetry was detected.

Moreover, the apparent turbulence observed in the lumen is less likely than laminar flow to be substantially and systematically altered by the presence of a narrow probe. That the probe itself was a major source of turbulence also seems contradicted by the observed central jet effects detected at low-TGI rates, despite high-bias flows passing over the probe.

In contrast, the sampling gas flow of 0.3 l/min has a higher potential for distorting gas within the tracheal lumen. Ambient gas within the trachea will be drawn toward the sampling probe orifice, creating geometric distortion within the region from which sampled gas is drawn. Such distortion is minute when both bias and TGI flows greatly exceed the sampling flow; however, as bias and TGI flows decrease, the volume of the sampled region will increase. As a first-order approximation, we define the sampled volume as a space centered on the sampling orifice for which the rate of gas entering it from bias and TGI sources equals the flow drawn out of it, 0.3 l/min. Enlargement of the sampled volume compromises the ability to resolve small details such as TGI jet effects, a problem that becomes a significant source of distortion when the radius of the sampled region exceeds the interval between samples (2 mm). To prevent distortion of any focal features that may be present, such as a TGI jet, two conditions must be met. First, if the probe is outside the jet, the gas flow into the sampled region must be supplied exclusively by the local bias flow, so that gas from the nearby jet is not aspirated. Conversely, if the probe is within the jet, the sampling flow should be supplied exclusively by the jet. If the jet is assumed to be concentrated, having a cross-sectional radius of no more than 3 mm, then even a low total TGI flow of 1 l/min would be expected to deliver more than 0.3 l/min into a radius of 2 mm. The bias flow, distributed over a larger cross-sectional area, is, therefore, the limiting characteristic for determining the sample radius. A model of the problem (see APPENDIX) indicates that a bias flow of 2.5 l/min produces a sampled radius of 2.4 mm, whereas a bias flow of 5 l/min reduces the radius to 1.7 mm. We conclude that “smearing” of our data probably exists for bias flows of 1 l/min and, to a lesser extent, 2.5 l/min. At greater flows, the distortion is finer than the sampling resolution. As samples are separated longitudinally by 10 mm, measurement of penetration distance should be unaffected by sampling flow distortion.

In conclusion, we find evidence in our model that forward-directed TGI not only washes the ETT and ventilator tubing proximal to the site of injection, but also projects distally into a substantial portion of the central airways. Surprisingly, “jet” behavior was minimal, and, in three different models, TGI gas behavior was not highly geometry dependent.

APPENDIX: MODELING THE DISTORTION PRODUCED BY THE SAMPLING GAS FLOW

The volume sampled by the probe is approximated by a sphere of radius \( r \), with a frontal area of \( \pi r^2 \). Bias-flow gas is assumed to have laminar flow characteristics, and distortion is assumed to be limited to the interior of this sphere. Therefore, bias-flow gas enters the sphere only over its frontal cross-sectional area, \( \pi r^2 \). Bias flow is considered to be evenly distributed over the tracheal cross section, so that the bias flow entering the sampled region is

\[
\text{Flow}_{\text{bias}} \left( \frac{\pi r^2}{\text{Area}_{\text{trachea}}} \right)
\]

Setting the flow entering the sampled region equal to the sampling flow drawn from it yields

\[
\text{Flow}_{\text{bias}} \left( \frac{\pi r^2}{\text{Area}_{\text{trachea}}} \right) = \text{Flow}_{\text{sampling}}
\]

\[
\text{Flow}_{\text{bias}} \left( \frac{\pi r^2}{1.54 \text{ cm}^2} \right) = 300 \text{ cm}^3/\text{min}
\]

\[
r = \frac{147 \text{ cm}^3/\text{min}}{\pi \cdot \text{Flow}_{\text{bias}}}
\]
Solving for \( r \) as a function of bias flow, thus

\[
\begin{array}{c|c}
\text{Flow}_{\text{bias}}, \text{ cm}^3/\text{min} & \text{r, cm} \\
1,000 & 0.38 \\
2,500 & 0.24 \\
5,000 & 0.17 \\
\end{array}
\]

This study was supported by National Institutes of Health Specialized Center of Research Grant N-071. J. R. Hotchkiss was supported by American Heart Association Grant SDG930184N.

REFERENCES


