The effect of gas density on glottal vibration and exit jet particle velocity

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Although theoretical studies include a term for gas density in their mathematical descriptions of glottal aerodynamics, the effect of gas density on glottal vibration has not been examined empirically. In this study, an *in vivo* canine model was used to evaluate the effect of gas density on glottal vibration by comparing phonation with air and helium. With gas flow and nerve stimulation held constant, phonation with helium resulted in an increased exit jet particle velocity for helium (45 m/s) compared to air (34 m/s). However, the measured increase in helium velocity was less than predicted by a proportional relationship between transglottal pressure and dynamic pressure. This difference could be due to a change in the constant of proportionality or in the dynamic pressure loss coefficient associated with the use of helium.

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INTRODUCTION

Because vocal fold oscillations are caused by the flow of air through the glottis (Ananthapadmanabha and Gauffin, 1983), aerodynamic forces in phonation are of considerable theoretical and practical interest to aerodynamic engineers as well as voice scientists. Titze (1986) has described several fundamental properties of air that in theory determine the characteristics of vocal fold vibration. These properties (including flow rate, pressure, velocity, density, and viscosity) interact with the vocal folds to create a mucosal wave. Several authors have measured the effect of glottal airflow rate, subglottic pressure (SGP), and exit jet velocity on vocal fold vibration (Ladefoged and McKinney, 1963; Tanaka and Gould, 1985; Berke *et al.*, 1987; Iwata, 1988), although the independent influence of these factors on the mucosal wave has been difficult to study due to their complex covariant nature. Studies of these interactions in humans are further complicated by the need to control for laryngeal adjustments made by the subject.

The effects of gas density on speech were investigated in the 1960s in studies of helium speech (MacLean, 1966; Holywell and Harvey, 1963; Fant and Lindqvist, 1968; Beil, 1962). An enriched helium environment reduces the high nitrogen content of air and prevents nitrogen narcosis and decompression sickness during deep sea diving. However, intelligibility is poor in this environment, and vocal quality is altered. The altered vocal quality has been attributed to increases in the first, second, and third formants in the helium-rich environment; fundamental frequency ($F0$) varied little. Holywell and Harvey (1963) believed that the shift in formants was due to the velocity of sound in a vocal tract filled with the helium gas mixture.

While air density has been estimated to be relatively constant throughout the glottal cycle (Schlichting, 1968), the effects of gas density and viscosity on glottal vibration and particle velocity have not been examined. The relation between pressure across the glottis and volume velocity is given by a relation between transglottal pressure and gas density (Ishizaka and Matsudaira, 1972):

$$P_{\text{Trans}}=(K/2)rQ_g^2+CQ_g, \tag{1}$$

where P_{Trans} is the transglottal pressure, r is the gas density, Q_g is the volume velocity through the glottis, K is the dynamic pressure loss coefficient, and C is the laminar viscous loss coefficient.

While this relation holds strictly for static glottal configurations, it will be assumed that it applies to P_{Trans} and Q_g averaged over complete glottal cycles. The constants K and C can be measured and have also been derived for models (e.g., Ishizaka and Matsudaira, 1972). Both depend on geometry of the glottis. C is also determined by the dynamic viscosity of the gas and the velocity profile. However, K incorporates the effects of dynamic pressure head loss due to the formation of rotational fluid motion (i.e., vorticity) that is associated with turbulence. Thus K may depend on other properties of the gas, particularly density and viscosity, because of their effect on the Reynolds number. The relative importance of the dynamic pressure loss term and the laminar viscous loss term in Eq. (1) depends on geometry, with the laminar loss term most important when the vocal folds are nearly closed. Note that Eq. (1) can be rewritten in terms

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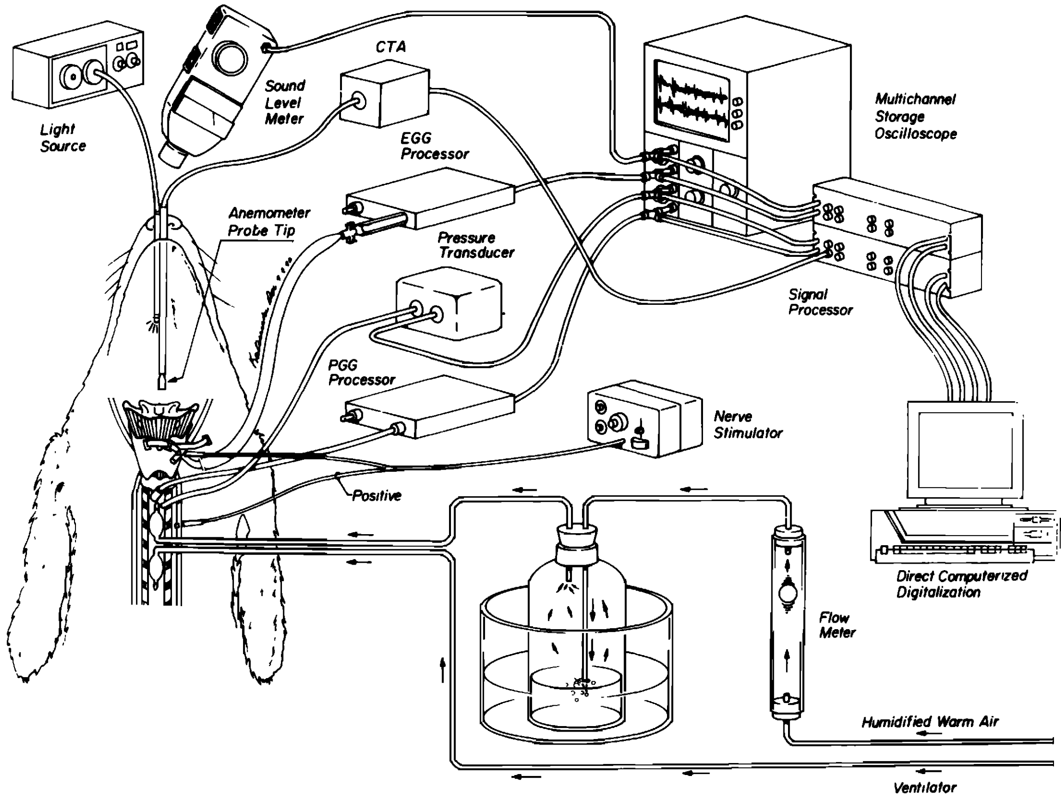

FIG. 1. The *in vivo* canine preparation.

of cross-sectionally averaged particle velocity in the glottis, since this quantity is equal to the volume flow through the glottis divided by the cross-sectional area of the glottis.

In the present study, a constant temperature anemometer (CTA) was used in an *in vivo* canine model of phonation to evaluate the effect of gas density on phonation. SGP, exit jet particle velocity, and glottal vibration were measured for phonation with air and helium, while gas flow rates and levels of recurrent laryngeal nerve (RLN) and superior laryngeal nerve (SLN) stimulation were held constant. In switching from air to helium, the gas density decreases by a factor of 7 (air=1.161 g/m^3 and helium=0.160 g/m^3) while the viscosity of the gases (air=18.6 μPa s and helium=20.0 μPa s) remains fairly constant. Thus an increase in average glottal particle velocity would be expected, assuming a fixed transglottal pressure. This prediction further assumes that the gas density does not affect K or C through its effect on the flow of gas or the vibratory pattern of the vocal folds.

I. METHODS

A. *In vivo* canine model

The *in vivo* canine model of phonation (Fig. 1) has been described in detail by Berke *et al.* (1987). A 20-kg mongrel dog was premedicated with acepromazine intramuscularly. Intravenous sodium thiopental was administered to a level of corneal anesthesia, and additional sodium thiopental was used to maintain this level of anesthesia throughout the experiment.

The dog was placed supine on the operating table and the trachea was exposed from the sternal notch to the hyoid bone through a midline incision. Both recurrent and superior laryngeal nerves were identified and preserved. A low tracheotomy was performed at the level of the suprasternal notch, through which an endotracheal tube was passed to allow ventilator-assisted respiration. A second tracheotomy was performed in a more superior location. A cuffed endotracheal tube was passed through this second tracheotomy in a rostral direction and was positioned with the tip 10 cm below the vocal folds. The cuff was inflated to seal the trachea.

Air or helium was passed through the rostral endotracheal tube from a compressed gas tank. The gases were humidified and heated by bubbling through 5 cm of heated water so that the temperature of the gas was 37 °C when measured at the glottal outlet. Phonation was produced with a constant flow of 388 cc/s. Flow rates were controlled by a valve at the laboratory wall outlet and measured with a U-tube flow meter (Gilmont Instruments, model F1500; Great Neck, NY) calibrated for air and helium using gas calibration equations provided by the manufacturer.

One-cm segments of the recurrent and superior laryngeal nerves were isolated. Harvard miniature electrodes were applied around each nerve. Separate constant voltage nerve stimulators (WR Medical Electronics Co., St. Paul, MN: model S2LH) provided stimulation to the recurrent and superior laryngeal nerves bilaterally. Nerves were stimulated at 70 Hz with 1.0-mV intensity for 1.5 ms.

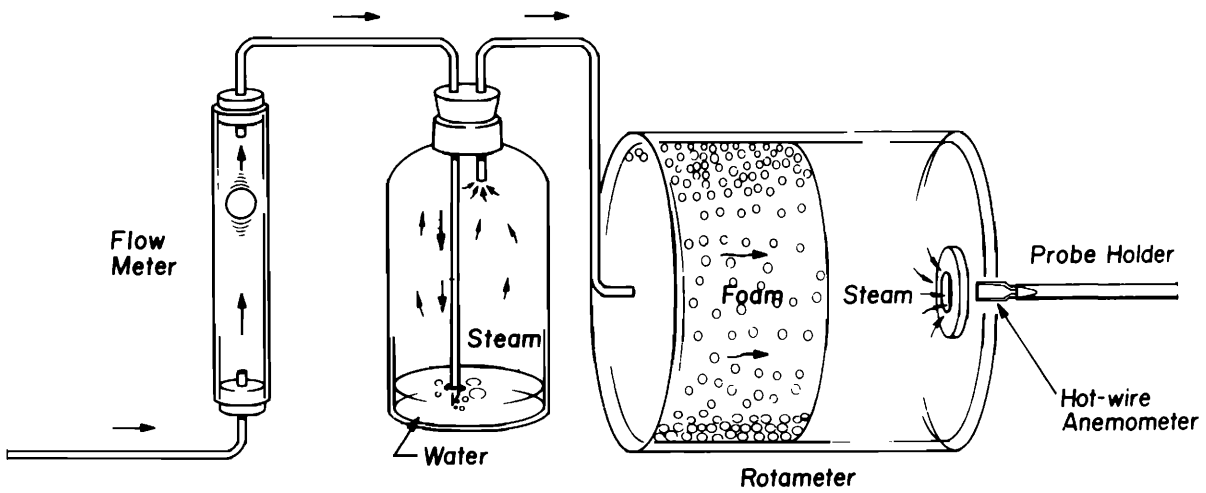

FIG. 2. Schematic of the constant-temperature anemometer calibration setup for air and helium with (1) Gilmont flow meter, (2) constant-temperature humidifier, (3) jet settling chamber with packing of open cell foam, (4) outflow jet, and (5) anemometer probe tip.

B. Glottographic and pressure measurements

The photoglottographic (PGG) measurement system consisted of a single-element photovoltaic sensor with an active area of 50 mm^2 (Centronic OSD 50-2), followed by a preamplifier with a bandwidth of 5 kHz. The PGG light sensor was placed on the trachea 3 cm below the larynx. A halogen flashlight provided supraglottic illumination. Electroglottographic (EGG) signals were obtained with a Synchrovoice electroglottograph. The EGG electrodes were placed in direct contact with the thyroid cartilage; the reference electrode was sutured to the sternocleidomastoid muscle.

The PGG and EGG signals were used to calculate the open quotient (OQ) and speed quotient (SQ) (Childers *et al.*, 1990; Berke *et al.*, 1987). The OQ was defined as the ratio of the open period to the duration of the entire glottal cycle. The open period was defined as the time from the peak of the positive deflection of the differentiated EGG (dEGG) signal (corresponding to the opening of the upper margin of the vocal folds) to the peak of the negative deflection of the dEGG signal (corresponding to the closing of the lower margin of the vocal folds). The closed period was defined as the total glottal period minus the open period. The SQ was defined as the ratio of the opening phase to the closing phase. The opening phase was defined as the time interval from the opening of the upper vocal fold margin (peak of the upward deflection of the dEGG) to the maximal glottal width (peak of the PGG waveform). The closing phase was defined as the open period minus the opening phase. Finally, fundamental frequency was calculated using the reciprocal of the mean period of ten consecutive cycles of the PGG waveform.

SGP was measured using a Millar Mikro-Tip catheter pressure transducer (model SPC-330, size 3F) passed rostrally through the superior tracheotomy and placed 5 cm below the glottis. The pressure transducer was calibrated before the experiment against a mercury manometer. The peak SGP was measured as the average of ten consecutive SGP peaks during each phonatory trial for air and helium. The PGG, EGG, and SGP signals were low-pass filtered at 3 kHz and digitized at 10 kHz, using a 12-bit analog-to-digital converter. The digitized signals were analyzed using commercially available software (C-SPEECH).

C. Constant-temperature anemometry

Exit jet particle velocity was measured with a Dantec CTA (Mahwah, NJ; type 56C01). The hot-wire anemometer probe tip (Dantec, type 55R01) was held 1 cm superior to the glottis, thus providing a measure of exit jet particle velocity (not glottal particle velocity). The probe tip could not be placed at the glottal level to measure glottal particle velocity directly, because such placement would prevent normal vibration of the vocal fold and would damage the probe tip. The probe was held in the midline midway between the anterior and posterior commissure by a micromanipulator mounted on a tripod at the head of the operating table. The probe had an active length of 1.25 mm and was quartz coated for use in a humid environment.

The CTA probe was calibrated separately for air and helium at the beginning and end of the experiment using a rotameter (Fig. 2). The rotameter was independently calibrated against a mercury U-tube manometer to determine the dynamic head of saturated air and helium (Bradshaw, 1964). The rotameter had a 3-mm-diameter opening with a converging throat to avoid airflow separation and to provide a uniform velocity across the opening. The gas was humidified and heated for calibration through the rotameter, so that the temperature of the gas was 37 °C when measured at the outlet of the rotameter.

The digitized experimental anemometry signals were converted from volts to m/s for each trial using a third-order polynomial calibration curve, which provided excellent fit to the original data (correlation coefficient for helium and air: $r^2=0.98$ and $r^2=1.00$, respectively). Peak velocity was measured for ten consecutive glottal cycles for each trial. The relationship of peak velocity to the glottal cycle was determined by measuring the time from the most open portion of the glottal cycle (peak PGG) to the peak of the velocity waveform for each gas.

TABLE I. Effect of helium and airflow on subglottic pressure, velocity, $F0$, OQ, SQ, and peak PGG to peak velocity.

	Subglottic pressure (mm Hg)	Peak velocity (m/s)	Minimum velocity (m/s)	$F0$ (Hz)	OQ	SQ	Peak PGG to peak velocity (ms)
Helium	70	45	9	277	0.52	1.09	0.06
Air	62	34	4	304	0.50	1.23	0.01

D. Experimental design

Five trials were performed for each gas. To control for effects of gas presentation order, air-to-helium and helium-to-air trials were alternated. Air and helium were delivered from compressed gas tanks; the gas inflow lines were purged for 30 s before each trial to eliminate admixture of air and helium. Constant levels of gas flow (388 cc/s), RLN stimulation (1.0 mV), and SLN stimulation (1.0 mV) were maintained throughout the experiment. Short trials (2.8 s) were used to minimize the confounding effect of intrinsic laryngeal muscle fatigue across trials.

The EGG and PGG signals, subglottal pressure, velocity, and acoustic waveforms were digitized at 10 kHz and low-pass filtered at 3 kHz for each experimental trial. For each trial, ten segments of stable phonation were selected. Measurement was then performed on ten consecutive vocal cycles within each segment. Means were calculated across these ten cycles and were subsequently used in statistical analysis.

II. RESULTS

A. Effects of gas type on glottal vibration

Mean values of peak SGP, peak velocity, minimum velocity, $F0$, OQ, SQ, and the time interval separating peak PGG values and peak velocity are given for each gas in Table I. Figures 3 and 4 show sample velocity waveforms for helium and air, respectively, along with the associated EGG, PGG, and SGP tracings. Note the "double peaked" shape of both velocity waveforms. The second peak may be caused by increased velocity associated with the closing of the glottis from the lower margin to the upper margin of the vocal folds (Berke *et al.*, 1987).

A one-way multivariate analysis of variance (MANOVA) examined the effects of gas type on each dependent measure. Significant univariate effects were found for SGP, peak and minimum velocity, $F0$, and SQ [SGP: $F(1,88)=27.29$, $p<0.05$; peak velocity: $F(1,88)=5.01$, $p<0.05$; minimum velocity: $F(1,88)=162.96$, $p<0.05$; $F0$: $F(1,88)=643.59$, $p<0.05$; SQ: $F(1,88)=37.40$, $p<0.05$). A multivariate test also showed significant differences between gases [Wilks' lambda=0.043; $F(7,82)=258.68$, $p<0.05$]. No significant univariate effect of gas type was observed for OQ or for the time interval separating peak PGG values and peak velocity (OQ: $F(1,88)=2.59$, $p>0.05$; time interval: $F(1,88)=2.70$, $p>0.05$). These variables were dropped from subsequent analyses.

Several dependent measures were moderately but significantly correlated. In particular, SGP was correlated with both peak and minimum velocity (peak velocity: $r=0.41$; minimum velocity: $r=-0.56$; $p<0.05$ adjusted for multiple comparisons where r is the correlation coefficient), and $F0$ was correlated with minimum velocity and SQ (minimum velocity: $r=0.77$; SQ: $r=0.43$; $p<0.05$ adjusted for multiple comparisons). A multivariate analysis of covariance (MANCOVA) was used to adjust for these correlations. Peak velocity, minimum velocity, and SQ were treated as dependent measures in this analysis, and $F0$ and SGP were included as covariates. A significant effect of gas type on SQ

FIG. 3. Alignment of the peak of the velocity and PGG waveform for helium gas.

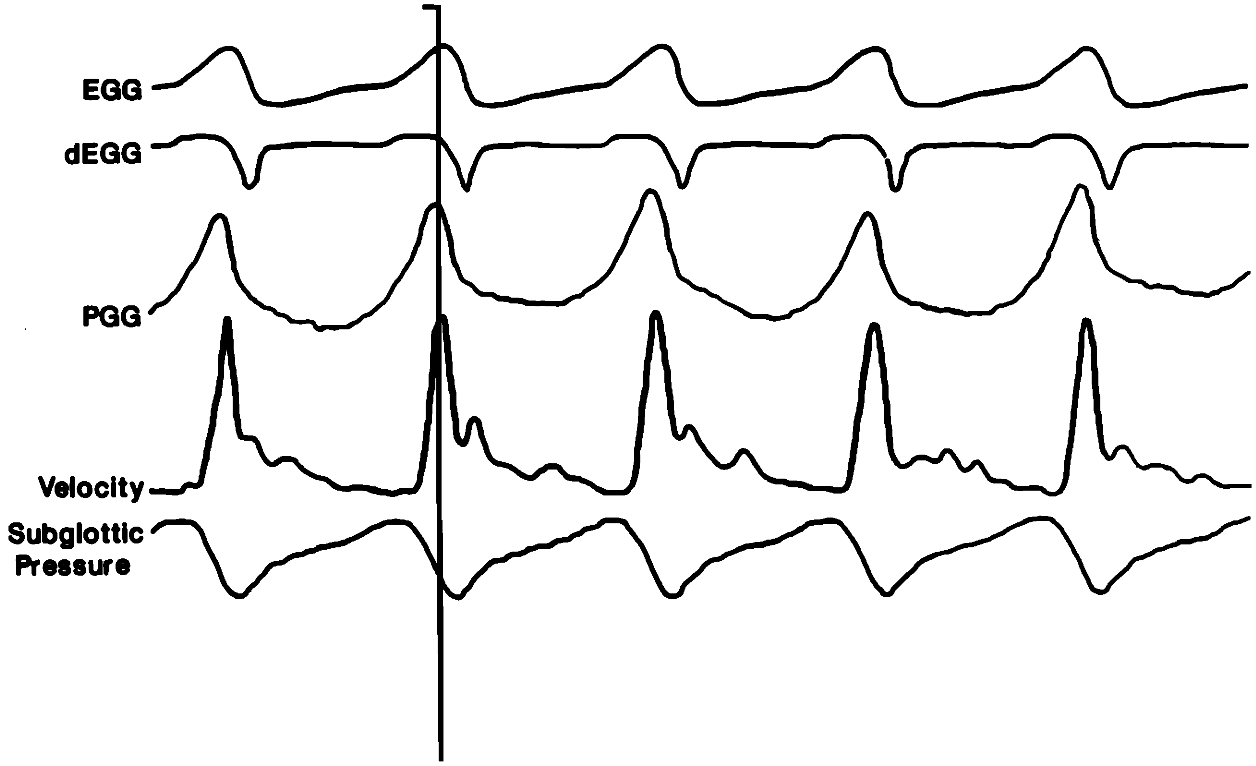

FIG. 4. Alignment of the peak of the velocity and PGG waveform for air.

was observed after controlling for differences in $F0$ and SGP [$F(1,96)=6.45$, $p<0.05$]; however, no significant effects on peak or minimum velocity were observed [peak velocity: $F(1,96)=2.67$, $p>0.05$; minimum velocity: $F(1,96)=0.52$, $p>0.05$]. Thus differences in $F0$, SGP, and particle velocity are not independent effects in this study.

III. DISCUSSION

Under the restrictive assumptions stated in the Introduction, the hypothesis that glottal particle velocity would be greater in helium than it was in air for a given transglottal pressure was examined. This statement was based on Eq. (1), assuming that the loss coefficients are not a function of gas type and that the glottal area functions for air and helium were the same. If the laminar viscous loss coefficients C are assumed to be negligible, then the ratio of cross-sectionally averaged glottal particle velocities in the two gases can be written as

$$\frac{V_{\mathrm{He}}}{V_{\mathrm{air}}}=\sqrt{\frac{r_{\mathrm{air}}P_{\mathrm{TransHe}}}{r_{\mathrm{He}}P_{\mathrm{TransAir}}}}, \qquad (2)$$

where V is the cross-sectionally averaged particle velocity, r is the gas density, and P_{Trans} is the transglottal pressure.

If the ratio of measured maximum exit jet particle velocities is further assumed to be equal to the ratio of cross-sectionally averaged glottal particle velocities, then the measured maximum helium exit jet particle velocities were substantially lower than those predicted by this simplified equation. The measured maximum exit jet particle velocity was 34 for air and 45 m/s for helium. Based on the density and transglottal pressure differences between the trials with air and those with helium, the maximum exit jet particle velocity predicted from Eq. (2) for helium is 97, vs 34 m/s for air. The expected exit jet velocity during helium trials would be just 2 m/s greater than those for air, if only transglottal pressure differences were effective. However, part of the increase in exit jet particle velocity with helium is due to the combination of a constant overall volume flow and a decreased $F0$, because more flow per open phase of the glottal cycle is needed to sustain the volume flow. It must be concluded that one or more of the assumptions used in deriving Eq. (2) (the ratio of maximum exit jet particle velocities as an index of the ratio of overall glottal particle velocities, the constant area function, a constant K, or the negligibility of the linear viscous loss) is incorrect.

Berke *et al.* (1989) identified a gradient of values in the maximum exit jet velocity of air, with the highest values located near the anterior commissure (69–81 m/s) and the lowest at the posterior commissure (19–56 m/s). The maximum exit jet velocity for air obtained midway between the anterior and posterior commissure in the present study is consistent with those obtained at the same site by Berke *et al.* The timing of the maximum of the velocity waveform relative to the maximum of the PGG waveform (the most open portion of the glottal cycle) is also consistent with the findings of Berke *et al.* Figures 3 and 4 demonstrate that maximum velocity occurs slightly prior to peak glottal opening (i.e., peak PGG) for both air and helium (0.01 and 0.06 ms, respectively). The rise in the PGG waveform occurred prior to the brisk rise in the velocity waveform, due to the thinning of the vocal folds prior to horizontal opening. However, we cannot be sure that the ratio of measured maximum exit jet particle velocities is equal to the ratio of the cross-sectionally averaged glottal velocities for the two gases.

To evaluate the other assumptions, consider the resistance to flow in the glottal region of the two gases. Resistance is the ratio of the pressure change through the glottis to the volume velocity. From Eq. (1) this can be written

$$\frac{P_{\text{Trans}}}{Q_g}=\frac{K}{2}rQ_g+C. \tag{3}$$

The helium trials had a subglottal pressure of 70, compared to 62 mm Hg for air; both used the same volume flow. Thus resistance was 0.180 for helium and 0.160 mm Hg s/cc for air. Therefore either the viscous loss term is not negligible for both gases, or the turbulence loss coefficient K is greater for helium because of alterations in vibration pattern or kinematic viscosity (and hence Reynolds number). Because of the difference in density between the gases, maintaining the same resistance without an increase in viscous loss for helium would require that K be about 8× greater in helium than in air.

Some pressure head loss for helium might occur between the pressure transducer and the glottis. The possibility of substantially increased pressure loss in the trachea may be evaluated by computing the viscous loss in internal pipe flow. Expected pressure loss can be calculated as a function of Reynolds number and the dynamic head, $1/2rv^2$, where v is the cross-sectionally averaged particle velocity in the pipe (Landau and Lifshitz, 1959). The Reynolds number is calculated for each gas based on volume flow and tracheal radius (assumed to be 1 cm). The Reynolds number for air is 2000; the value for helium is 250. Based on these calculations, helium should show less loss than air through a smooth tube for a given volume flow. Thus the viscous friction loss through the trachea would not account for the observed increase in resistance when the helium is flowing. These calculations assume that airflow is turbulent and helium flow is laminar in the trachea, although this depends on wall roughness and flow entry conditions.

Thus the differences in resistance between the air and helium conditions should be due to differences in flow in the glottal region. Large increases in K could occur if the glottal area for helium were smaller for a given volume flow (Ishizaka and Matsudaira, 1972). This effectively means that the glottal particle velocity tends to be greater during helium phonation than during phonation in air. As previously discussed, no direct measure of glottal particle velocity was made; therefore this cannot be confirmed. Geometric factors, such as shape of the glottal channel, may also contribute to an increase in K for helium.

The differences in Reynolds number in the trachea could mean qualitative differences in flow characteristics occurred for the two gases. As already noted, the flow in the trachea could have been turbulent for air and laminar for helium through much of the glottal cycle. Thus the flow entry conditions into the glottis could have been substantially different. Further, the large differences in Reynolds numbers in the glottis could have large effects on boundary-layer separation properties, particularly in an unsteady environment (McGowan, 1994). Boundary-layer separation helps to determine pressure head loss and the value of K, which makes vocal fold oscillations possible (Ishizaka and Matsudaira, 1972; Titze, 1988).

With helium phonation, higher translaryngeal velocity and higher SGP both suggest increases in $F0$ should also occur (e.g., Titze, 1986). Authors examining helium phonation in humans have generally reported nonsignificant changes in $F0$. In the present study, $F0$ actually decreased for phonation with helium. This change in $F0$ is unique to the *in vivo* model of phonation, and may be due to the inability of the canine to compensate for the change in gas in the model, which used fixed levels of nerve stimulation. In contrast, humans are able to adjust RLN and SLN stimulation with the alterations in gas type, so glottal shape changes along with the viscosity and turbulence loss coefficients of Eq. (1).

In conclusion, the effects of gas density on phonation in the *in vivo* canine model of phonation were evaluated. With gas flow, RLN stimulation, and SLN stimulation held constant, phonation with helium resulted in an increase in particle velocity that was less than predicted by Eq. (2). The lower-than-predicted particle velocity in helium phonation may be explained by unknown changes in the turbulence loss coefficient K due to significant Reynolds number changes.

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