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CHARACTERIZATION OF FLOW-RESISTANT TUBES USED FOR SEMI-OCCLUDED VOCAL TRACT VOICE TRAINING AND THERAPY

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Abstract

Objectives—To characterize the pressure-flow relationship of tubes used for semi-occluded vocal tract voice training/therapy, as well as to answer these major questions: (1) What is the relative importance of tube length to tube diameter? (2) What is the range of oral pressures achieved with tubes at phonation flow rates? (3) Does mouth configuration behind the tubes matter?

Methods—Plastic tubes of various diameters and lengths were mounted in line with an upstream pipe, and the pressure drop across each tube was measured at stepwise increments in flow rate. Basic flow theory and modified flow theory equations were used to describe the pressure-flow relationship of the tubes based on diameter and length. Additionally, the upstream pipe diameter was varied to explore how mouth shape affects tube resistance.

Results—The modified equation provided an excellent prediction of the pressure-flow relationship across all tube sizes (6% error compared to the experimental data). Variation in upstream pipe diameter yielded up to 10% deviation in pressure for tube sizes typically used in voice training/therapy.

Conclusions—Using the presented equations, resistance can be characterized for any tube based on diameter, length, and flow rate. With regard to the original questions, we found that: (1) For commonly used tubes, diameter is the critical variable for governing flow resistance; (2) For phonation flow rates, a range of tube dimensions produced pressures between 0 and 7.0 kPa; (3) The mouth pressure behind the lips will vary slightly with different mouth shapes, but this effect can be considered relatively insignificant.

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Keywords

flow-resistant tubes; semi-occluded vocal tract; voice therapy; voice training; flow resistance; pressure drop; oral pressure

INTRODUCTION

The use of flow-resistant tubes or straws is one of many ways to create a semi-occlusion at the lips for the purpose of voice training and rehabilitation. A vital part of caring for the vocal instrument is performing vocal warm-ups before singing or speaking. As with any warm-up exercise, vocal warm-up is geared towards stretching the tissues and increasing blood flow, which helps to prevent vocal injury. Stretching of the vocal folds is accomplished by gliding to a high fundamental frequency (f_0), but a high f_0 with an open mouth and moderate intensity involve significant vocal fold collision and sometimes unstable voice quality. With a semi-occlusion at the mouth, the transglottal pressure is greatly reduced and the vocal folds can vibrate with low amplitude at high fundamental frequencies. If vocal injury has occurred, voice therapy with oral semi-occlusions can be employed to rehabilitate the voice and establish healthy phonation practices with better vocal fold adduction. While lip trills, tongue trills, nasal consonants, and voiced fricative consonants are all used effectively for voice training and therapy^{1–4}, the use of flow-resistant tubes is becoming increasingly popular because these semi-occlusions are controllable and repeatable due to specific tube dimensions.

The flow-resistance provided by a semi-occluded vocal tract (SOVT) produces an intraoral pressure above the glottis, which helps to push apart the top edges of the vocal folds.⁵ This pushing apart of the top edges reduces vocal fold collision.^{6,7} It has been shown to also balance activation of the cricothyroid and thyroarytenoid muscles.⁸ Yet another positive effect of SOVT is to lower the phonation threshold pressure^{9,10} by increasing vocal tract inertance.¹¹

The flow resistance of the tubes can be varied with different geometries. It has been hypothesized that an optimal tube is one that exhibits a resistance equal to the glottal resistance.¹² This creates a ratio of oral pressure to subglottal pressure of 0.5, which provides maximum aerodynamic power transfer from the source to the vocal tract.

While estimates of glottal resistance for any individual can be obtained¹³, measurement and characterization of the resistance provided by tubes has only been preliminary. Titze et al.¹⁴ made measurements of the pressure-flow relationship of several commercially-available plastic straws of different diameters, from which resistance was calculated (pressure divided by flow rate). Results were used to estimate lip and larynx resistance from oral pressure measurements on human subjects producing vowels using the straws. There remains a need for measurement of pressure-flow characteristics for a wider variety of tubes (i.e., more diameters and lengths) which will lead to development of a general equation that predicts tube resistance as a function of diameter and length. Such an equation can be used to select a tube to match a subject-specific glottal resistance and assess the relative benefit of using a tube matched to glottal resistance.

In this paper we characterize the relationship between pressure and flow, with their ratio being flow resistance, for tubes likely to be used in voice training and therapy. The major questions to be answered are: (1) What is the relative importance of tube length to tube diameter? (2) What is the range of oral pressures achieved with tubes that allow speech-like flow rates? (3) Does the mouth configuration behind the tubes matter? We study a wide range of tube diameters and lengths across a wide range of flow rates, in order to obtain an accurate pressure-flow characterization based on tube diameter and length for commonly used tubes and typical phonation flow rates. In addition, we address the influence of mouth shape on the pressure-flow relationship by including an upstream pipe with a specified diameter. Along with answers to the major questions, general equations for resistance as a function of flow rate, tube diameter, and tube length are presented.

METHODS

A setup was created to measure the pressure drop across a variety of tubes at stepwise increments in flow rate. The flow was driven by a compressed air source connected to a flow line. In line with the flow was a pressure regulator (Fairchild 10212), maintaining 13.8 kPa (2 psi) pressure upstream to protect the instrumentation downstream, a needle valve (Parker VSeries) to adjust flow rate, and an electronic mass flow meter (Omega FMA-A2323) to measure air flow rate. Leading from the flow meter was flexible PVC tubing, connected to a 30.5-cm (12") length of 1.91-cm (3/4") diameter rigid threaded PVC pipe at the end of the setup ("upstream pipe"). A flow straightener was constructed at the entrance of the upstream pipe to assure laminar flow. A pressure tap was placed approximately 2 cm upstream of the tube entrance and pressure was measured using a silicone pressure transducer (Omega PX137-001D). Tubes were secured to the end of the setup via a custom fixture, consisting of a circular piece of 9.5-mm (3/8") thick rubber sheet with a hole cut in the center to insert the tube, placed in a PVC pipe cap with a hole in the top, which was then screwed onto the end of the PVC flow tube.

Pressure-flow measurements were obtained for a wide range of tube diameters and lengths. Standard round plastic tubing (Evergreen Scale Models) was used. Tube inner diameters that were studied included 1.8, 2.5, 3.3, 4.1, 4.9, 6.5, 8.1, and 9.7 mm. Each of these tubes was cut to lengths of 3, 6, 12, and 24 cm. The tubes were tested in randomized order by diameter and then by length. The experiments were repeated 3 times in different random orders. Flow was ramped up in increments of either 0.01, 0.05, or 0.10 L/s, depending on tube diameter. Smaller diameters required higher resolution in order to obtain a sufficient number of data points, as the pressure reached its upper limit at low flows. Flow was increased until it reached 1.50 L/s or until pressure reached 6.89 kPa (1 psi). These flow rates and pressures span the range expected for human phonation (0 – 1.0 L/s).

In addition to the 1.91-cm diameter upstream pipe, a 0.95-cm (3/8") diameter pipe and a 3.81-cm (1 1/2") diameter pipe were used to determine the influence of mouth shape on the pressure-flow relationship. Tubes were mounted on the end of the pipes in the same fashion as described above, and all diameters and lengths were tested once. The only exception was that the 9.7-mm tube could not be tested with the 0.95-cm upstream pipe, as it would create an expansion rather than a reduction.

Pressure and flow analog signals were read via an AD Instruments PowerLab (8/35) analog-to-digital converter, and the digital signal was then recorded with LabChart software. Approximately 1-second recordings at 1000 Hz were taken at each flow increment. MATLAB was used to process the LabChart data. Individual flow rate and pressure data points were found by averaging the recorded data over 0.65 sec, and the processed data was organized by diameter and length.

A goal of this study was to be able to describe the pressure-flow characteristics of flow-resistant tubes in terms of tube diameter and length. According to basic flow theory¹⁵, the pressure P at the tube entrance can be described in terms of flow rate (U in L/s), tube diameter (D in m), and tube length (L in m) by the relationship

$$\Delta P = C_1 \frac{\rho}{D^4} U^2 + C_2 \frac{\mu L}{D^4} U, \quad (1)$$

where ρ is air density (1.225 kg/m³), μ is air dynamic viscosity (1.983E-05 Pa·s), and C_1 and C_2 are constants that can be estimated from the literature or found empirically. The squared flow term represents pressure loss due to the inlet, exit, and length of hydrodynamic development in the tube. It is taken from the kinetic energy term in Bernoulli's equation and can be termed "kinetic loss". The linear flow term represents loss due to wall friction along the length of the tube. It depends on the dynamic viscosity of the fluid and can be referred to as "viscous loss".

Basic flow theory (Eq. 1) provided a starting point for describing the pressure-flow relationship; however, analysis of the experimental data revealed that the pressure-flow behavior varied somewhat differently with respect to L and D , and was more appropriately described by the modified equation

$$P = \left(A_1 \frac{L}{D^{X_1}} + A_2 \frac{1}{D^{X_2}} \right) U^2 + \left(B_1 \frac{L}{D^{Y_1}} + B_2 \frac{1}{D^{Y_2}} \right) U. \quad (2)$$

Coefficients on squared and linear flow terms have two components, one that varies linearly with L and one that is independent of L . Each has an inverse exponential relationship with D . Flow constants ρ and μ will not vary for the application to the human voice and are therefore absorbed into the other constants. For the squared flow term, constants A_1 and A_2 describe the linear relationship to L , and exponents X_1 and X_2 characterize the influence of D . Constants B_1 and B_2 and exponents Y_1 and Y_2 are similar parameters for the linear flow term coefficient.

Both the basic flow theory (Eq. 1) and the modified flow theory (Eq. 2) were applied to the experimental data. Coefficients of the flow terms were estimated using the generally observed relationships to L and D , and then more precise values were found by optimization. An evolutionary optimization routine was utilized in Excel in order to find the parameter values (C_1 and C_2 for Eq. 1; A_1 , A_2 , B_1 , B_2 , X_1 , X_2 , Y_1 , and Y_2 for Eq. 2), which minimized

the total percent error squared between experimental data points and the predicted pressure at the same flow rates.

Ultimately it is desired to obtain resistance from the pressure-flow measurements. This can be done by simple division. Resistance is the ratio of the pressure to the flow rate:

$$R = \frac{P}{U}. \quad (3)$$

Performing the division in Eqs. 1 and 2 results in the following respective equations for tube resistance:

$$R = C_1 \frac{\rho}{D^4} U + C_2 \frac{\mu L}{D^4}; \quad (4)$$

$$R = \left(A_1 \frac{L}{D^{X_1}} + A_2 \frac{1}{D^{X_2}} \right) U + \left(B_1 \frac{L}{D^{Y_1}} + B_2 \frac{1}{D^{Y_2}} \right). \quad (5)$$

RESULTS AND DISCUSSION

Figure 2 shows the pressure-flow data for all tube diameters and lengths. Data points represent an average of the three measurements with a 1.91-cm diameter upstream pipe. The data span much of the pressure-flow space in vocalization, allowing for an accurate prediction of the pressure-flow relationship across the range of tube diameters and lengths. The curves appear to follow a second-order polynomial, as predicted by flow theory. They vary linearly with L and exponentially with D . It is clear from the data that diameter plays a more influential role in determining pressure than length, as changes in length result only in small shifts of the pressure-flow curve within a cluster determined by diameter. For example, at a 0.5 L/s flow rate, doubling the length of a 4.9 mm diameter tube from 6 cm to 12 cm increases the pressure on the order of 20%, while doubling the diameter of a 12 cm long tube from 3.3 mm to 6.5 mm reduces the pressure by a factor of 10. In general, the data show that any desired pressure (in the feasible and expected range of about 0 to 7 kPa) can be achieved in the appropriate flow range (0 – 1 L/s) with the correct combination of tube diameter and length. Higher pressures at appropriate flow rates were best achieved with the tubes ranging from 2.5 to 4.9 mm in diameter.

Prediction with Basic Flow Theory

Average experimental data are shown again in Figure 3, separated into individual plots for each tube diameter. Error bars representing one standard deviation ($n=3$) are provided to show variation in the experimental pressure measurements. Variation was also present in the flow measurements, due to operator bias (i.e., flow measurements were not at exact incremental values due to limitations in being able to obtain exact values); however, these were shifted to exact incremental values and corresponding pressure values were corrected

based on a polynomial curve fit to the pressure-flow data for each case. Thus, the bias in the flow was nearly eliminated so that the error in the pressure data points represents only random error. The repeated measures were remarkably precise, and the random error was small for all cases.

The solid lines in Figure 3 also show pressures curves predicted by basic flow theory (Eq. 1). Optimization for the best fit across the entire data set (minimization of percent error squared) yielded the values listed in Table I. Hence, the pressure-flow relations were characterized by the equation:

$$P = \left(1.4496 \times 10^{-6} \frac{\rho}{D^4} \right) U^2 + \left(0.1752 \frac{\mu L}{D^4} \right) U. \quad (6)$$

Different colors in Figure 3 represent different tube lengths. The tube resistance is given by:

$$R = \left(1.4496 \times 10^{-6} \frac{\rho}{D^4} \right) U + \left(0.1752 \frac{\mu L}{D^4} \right). \quad (7)$$

The basic flow theory gave reasonably close approximations to the experimental data for the cases investigated. There were, however, some significant discrepancies, the most noticeable of which occurred for the 1.8-mm diameter tubes. Here, the theoretical curve underestimated the measured pressure, with a deviation of 1.12 kPa (17.2%) at 0.06 L/s for the 3-cm length. The difference increased with decreasing length, reaching 2.62 kPa (38.7%) at 0.13 L/s for the 24-cm length. An overestimate of the data occurred for the 8.1-mm diameter tubes, the greatest of which was observed for the 3-cm length, with a difference of 220 Pa (29.5%) at maximum flow. Two other more general trends were exhibited. First, the theoretical curve consistently underestimated pressure of the 24-cm length tubes for diameters ranging from 3.3 to 6.5 mm. This underestimation was as much as 1.0 kPa (16%) for the 4.1- and 4.9-mm diameter tubes. Second, for tubes greater than 4.1 mm in diameter, the theoretical curve consistently overestimated pressure of the 3- and 6-cm length tubes. The greatest magnitude deviation among these cases (after the 8.1-mm diameter case) was 0.56 kPa for the 4.9-mm diameter, 6-cm length tube. The highest percentage deviation was 20.9% for the 6.5-mm diameter, 3-cm length tube. A quantitative comparison between the measured points and corresponding predicted pressures gave an average absolute error of 13% for the entire dataset.

Predictions from Modified Flow Theory

Figure 4 shows the predicted pressure-flow curve from the modified flow theory (Eq. 2). Optimal parameter values for this characterization are also provided in Table I. The pressure and resistance are as follows:

$$P = \left(3.7631 \times 10^{-7} \frac{L}{D^{4.4997}} + 1.0268 \times 10^{-6} \frac{1}{D^{4.0416}} \right) U^2 + \left(3.9913 \times 10^{-9} \frac{L}{D^{5.0089}} + 8.0169 \times 10^{-7} \frac{1}{D^{3.7696}} \right) U; \quad (8)$$

$$R = \left(3.7631 \times 10^{-7} \frac{L}{D^{4.4997}} + 1.0268 \times 10^{-6} \frac{1}{D^{4.0416}} \right) U + \left(3.9913 \times 10^{-9} \frac{L}{D^{5.0089}} + 8.0169 \times 10^{-7} \frac{1}{D^{3.7696}} \right). \quad (9)$$

The modified flow theory was, overall, an excellent fit to the experimental data set. Quantitatively, the average absolute percent error for all the data was found to be 6%. The most obvious errors were for the 1.8 mm and the 8.1 mm diameter cases. For the 1.8-mm diameter tube, Equation 8 underestimated the experimental pressure for all lengths. The underestimation was 1.0 kPa, or a little more than 15%, for the 12- and 24-cm lengths at maximum flows. For the 8.1-mm diameter tube, on the other hand, an overestimation occurred for all lengths, with a maximum error of 0.16 kPa (13.5%) for the 24-cm case at a flow of 1.5 L/s.

General Summary of Pressure-Flow Characterization

The reasons for discrepancy between the experimental data and the predicted pressures are either experimental error or limitations in the equations. In the case of the 1.8-mm diameter tube, pressure was underestimated by both the basic and the modified flow theories. The predictions may begin to break down with small diameters. It is also plausible that there might be measurement errors due to inherent inaccuracy at significantly low flow rates (lowest 10% of range). As for the somewhat unique discrepancy with the 8.1-mm diameter tube, the fact that the equations overestimate the pressure for all tube lengths, coupled with the observation that the equations provide better fits above and below this one case (evidence that the relations do not begin to break down in this range), suggest that there was some kind of systematic experimental error. It was likely in the bench setup (e.g., irregularity in rubber insert used to mount tubes).

Despite the small discrepancies, the flow theory can be considered acceptable for describing the pressure-flow relationship of the tubes. The modified equation clearly gave a generally accurate description of the pressure-flow behavior. The maximum deviation of about 15% is minimal, and for typical flows the characterization provided a much more accurate estimate of the pressure drop across the tube. Moreover, the larger discrepancies for either equation fell outside of the range of tubes most commonly used for voice training and therapy (about 2 to 6 mm). A remaining issue, however, is the mouth configuration behind the tube, which the following data addresses.

Upstream Pipe Representing the Mouth Area

Figure 5 shows the results for three upstream pipe diameters. Along with the average data for the original 1.91-cm diameter, data are plotted for both a smaller diameter (0.95-cm) and a larger diameter (3.81-cm). For clarity, only the data for a tube length of 6 cm are plotted; results were similar for all other tube lengths.

For the three smallest tube diameters (1.8 mm to 3.3 mm), the pressure for the larger upstream pipe is closely matched with that of the original upstream pipe. For tube diameters greater than 3.3 mm, the larger upstream pipe yielded slightly increased pressures over the original pipe. The maximum deviation was observed with the 4.9-mm diameter tube, with an increase of 0.43 kPa at 1.5 L/s (9% difference). Although the magnitude of the pressure increase was less for tube diameters greater than 4.9 mm, the percentage increase was greater (10–20%). The effect was opposite for the smaller upstream pipe, which generally exhibited lower pressures than for the original pipe. This was noticeable for the 1.8-mm diameter tube and for tubes with diameters greater than 4.1 mm. The effect gradually increased in both magnitude and percentage as tube diameter increased from 4.9 to 8.1 mm. The greatest deviation occurred with the 8.1-mm diameter tube, with a difference of 0.26 kPa (31.5%).

These results can be partially explained in terms of two flow resistances in series. For a given flow, as the upstream pipe becomes wider, a larger portion of the combined pipe-tube pressure drop is across the tube. On the other hand, if the upstream pipe becomes smaller, its resistance increases and less pressure is dropped across the tube. This was generally observed. Following this reasoning, however, it would be expected that pressure would increase for the 1.8-mm diameter tube with a larger upstream pipe, which was not observed. Regardless of the explanation of one anomaly, the effect of upstream diameter was insignificant with the smallest diameter tubes.

It is important to also comment on the pressure deviation found for the large 8.1-mm diameter tube attached to a small diameter upstream pipe. This is noteworthy because the tube diameter was almost the same as the upstream pipe diameter (0.95 cm). The tube to upstream pipe diameter ratio was 0.85. As the tube diameter continues to approach the upstream pipe diameter, an effective tube lengthening will occur, with a significant percentage decrease in pressure drop across the actual tube length.

A final note regarding all of the results presented above is that tube entrance shape also plays a role in determining pressure. Different pressures might have occurred with different shapes immediately before the tube entrance. The experiments in this study employed a square reduction, which theoretically creates the greatest pressure drop of any area reduction shape. The mouth may provide a more gradual reduction in area, resulting in less resistance. However, differences in pressure loss due to entrance shape are considered minor corrections and should not affect the estimate significantly.

CONCLUSIONS

This study quantified the pressure-flow relations of a variety of tubes that may be useful for semi-occluding the vocal tract for voice training and therapy. Empirically-derived equations were developed for pressure and flow resistance at the lips. Modified equations provided corrections to a basic flow theory that predicts a kinetic term at entry to the tube and a viscous term that is length-dependent. The modified theory is applicable regardless of what typical mouth shapes might occur. Thus, resistance can be characterized for any tube based solely on diameter, length and flow rate.

The first question posed in the Introduction, *what is the relative importance of tube length versus tube diameter*, has been answered. Reducing the tube diameter by a factor of two (e.g., from 5.0 mm to 2.5 mm) increases the resistance by a factor ranging from 4 to 10, depending on flow and length. Increasing the tube length by a factor of two (e.g., from 6.0 cm to 12 cm) increases the resistance by only about 10–20%, but this applies only to diameters greater than 2.5 mm. For small diameters (less than 2.5 mm), length increase is as effective as diameter decrease in raising the resistance. Thus, for typical tubes or straws in usage, diameter is the critical variable for governing flow resistance, and therewith oral pressure. As an example, an appropriate diameter for producing an oral pressure of approximately 1.0 kPa with a flow of 0.1 L/s would be 2.5 mm, with a tube length of 6–12 cm.

The second question that was posed, *what is the range of pressures achievable with flow rates typical in speech-like phonation*, also has been answered. For typical 0 – 0.5 L/s flow rates in phonation, a range of tube dimensions produced a range of pressure between 0 and 7.0 kPa.

With regard to the third question, *does the mouth configuration behind the tubes matter*, the answer is somewhat preliminary. Results from this study suggest that pressure-flow characteristics of tubes depend slightly on upstream pipe diameter for larger diameter tubes. With regard to flow-resistant tube phonation, this means that the mouth pressure behind the lips will vary slightly with different mouth shapes. This effect, however, can be considered small, since the magnitude of the variation in pressure with different upstream pipes was relatively insignificant. It became more significant as tube diameter approached the upstream pipe diameter, but this is a case that can be avoided in practice by retracting the tongue. Large tube diameters, where this effect would be prevalent, fall outside of the range of commonly used flow-resistant tubes.

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Figure 1. Schematic of experimental setup for measuring pressure-flow characteristics of flow-resistant tubes, with detailed cross-section view of tube mounting apparatus.

Figure 2.

Experimental measurements of flow rate versus pressure for plastic tubes of various diameters and lengths. Different data point symbols differentiate tube diameters, while line styles differentiate tube lengths.

Figure 3.

Average experimental pressure-flow data ($n=3$) compared to basic flow theory (Eq. 1) with optimized parameter values from Eq. 6. Each plot is for an individual tube diameter, while colors denote different tube lengths. Error bars represent one standard deviation.

Figure 4.

Average experimental pressure-flow data ($n=3$) and prediction by modified flow theory with optimized parameter values (Eq. 8). Each plot is for an individual tube diameter, with colors denoting different tube lengths. Error bars represent one standard deviation.

Figure 5.

Average experimental pressure-flow data obtained using 1.91-cm diameter upstream pipe, compared to pressure-flow data obtained using upstream tubes with 0.95-cm and 3.81-cm diameters. Data shown for 6-cm length tubes. Various colors and markers represent different tube diameters and upstream pipe diameters, respectively.

Table I

Parameter values found by optimization to fit basic flow theory and modified flow theory equations to pressure-flow data of flow-resistant tubes.

Equation	Parameter	Optimized Value
<i>Basic Flow Theory</i>	C_1	1.4496×10^{-6}
	C_2	0.1752
<i>Modified Flow Theory</i>	A_1	3.7631×10^{-7}
	A_2	1.0268×10^{-6}
	X_1	4.4997
	X_2	4.0416
	B_1	3.9913×10^{-9}
	B_2	8.0169×10^{-7}
	Y_1	5.0089
	Y_2	3.7696