Characterization of Flow-resistant Tubes Used for Semi-occluded Vocal Tract Voice Training and Therapy

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Summary: Objectives. This study aimed 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 with 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, we can characterize resistance 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; and (3) The mouth pressure behind the lips will vary slightly with different mouth shapes, but this effect can be considered relatively insignificant.

Key Words: flow-resistant tubes–semi-occluded vocal tract–voice therapy–voice training–flow resistance.

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 toward 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, but a high fundamental frequency with an open mouth and moderate intensity involves 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. Although 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 owing to specific tube dimensions.

The flow resistance provided by a semi-occluded vocal tract 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 a semi-occluded vocal tract is that it lowers 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.

Although estimates of glottal resistance for any individual can be obtained,[13] 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 (ie, more diameters and lengths), which will lead to the 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? and (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 to

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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 (Figure 1). 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, Fairchild Industrial Products, Winston-Salem, NC), maintaining 13.8 kPa (2 psi) pressure upstream to protect the instrumentation downstream; a needle valve (Parker V Series, Parker Hannifin Corporation, Cleveland, OH) to adjust flow rate; and an electronic mass flow meter (Omega FMA-A2323, Omega Engineering, Inc., Stamford, CT) to measure air flow rate. Leading from the flow meter was flexible polyvinyl chloride (PVC) tubing, connected to a 30.5-cm (12″) long and 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, Omega Engineering, Inc., Stamford, CT). 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, DesPlaines, IL) 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

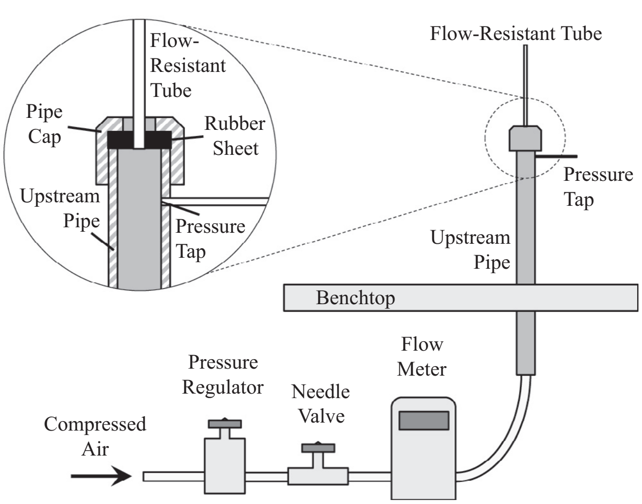

FIGURE 1. Schematic of experimental setup for the measurement of pressure-flow characteristics of flow-resistant tubes, with detailed cross-sectional view of tube mounting apparatus.

diameter and then by length. The experiments were repeated three 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 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 ADInstruments PowerLab 8/35 (ADInstruments Inc., Colorado Springs, CO) analog-to-digital converter, and the digital signal was then recorded with *LabChart* (ADInstruments Inc., Colorado Springs, CO) 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 seconds, and the processed data were 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 theory,[15] 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

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

where ρ is air density (1.225 kg/m^3), 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 the Bernoulli 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 (Equation 1) provided a starting point for the description of 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

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

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