An Exact Analytical Model for the Relationship Between Flow Resistance and Geometric Properties of Tubes Used in Semi-occluded Vocal Tract Exercises

*Andrey R. da Silva, †Ana Carolina Ghirardi, *Matheus Rutzen Reiser, and *Stephan Paul, *†*Florianópolis, Brazil*

Summary: Objectives. The purpose of this work was twofold. First, we aimed to develop an exact analytical model for tubes used in semi-occluded vocal tract exercises to gain a quantitative insight into the relationship between flow resistance and the tube's geometric parameters. The second goal was to provide an isometric resistance chart that can be used by clinicians to indicate either the diameter or the length of a tube, so as to provide the same flow resistance of a reference tube.

Methods. The theory for confined flows based on the Darcy-Weisbach equation was used to derive the analytical model, in which the friction factor was obtained by an explicit approximation with error smaller than 0.4%. The isometric resistance chart was generated with the analytical model, assuming the volume flow to be constant and equal to 0.4 L/s.

Results. The results obtained from the model agreed very well with both experimental and theoretical results from the literature, particularly for tubes longer than 6 cm and with inner diameters greater than 4.1 mm. In general, the analytical model slightly underestimates the back pressure for shorter and thinner tubes. For these cases, the maximum difference between analytical and experimental results corresponds to ≈5%.

Conclusions. Analysis of the equation terms indicated that the flow resistance is significantly more sensitive to variations in the inner diameter than to variations on the tube's length, which agrees with experimental results found in the literature. Moreover, the effect of the mouth configuration is negligible for tubes whose length are one order of magnitude greater the the inner diameter. Nevertheless, for short tubes the mouth configuration becomes a significant parameter and can be described by the ratio between the tube's inner diameter and the effective diameter of the patient's oral cavity. The analytical model presented in this work can be applied to the entire set of tube geometries found in clinical practice and constitutes a straightforward tool for designing tubes for semi-occluded vocal tract exercises with specific therapeutic purposes or patient needs.

Key Words: Semi-occluded vocal tract exercises−Voice therapy−Resonance tube phonation−Back pressure−Flow resistance.

INTRODUCTION

Semi-occluded vocal tract exercises (SOVTEs) are widely used in clinical settings for improving source-filter interaction and impedance adjustments of the vocal tract. The main result of such exercises is the augmentation of the vocal fold adduction by increasing the oral cavity pressure (back pressure) and decreasing transglottal pressure, which acts to push the vocal processes slightly apart.[1−4] Furthermore, because of the back pressure increase, semi-occlusions of the vocal tract provide patients with sensory feedback that will help them to speak and/or sing with improved vocal economy while reducing the amplitude of vocal fold vibration, which prevents mechanically induced tissue trauma.[1,5,6]

Several SOVTEs have been described, and their immediate and long-term effects on different acoustic and voice quality parameters have been widely reported.[2,3,5,7−13] Studies comparing the effects of different SOVTEs show that techniques involving phonation into straws or tubes of different materials, lengths, and diameters are highly beneficial in the prevention and treatment of voice disorders.[2,5,7,11,14−16] Short plastic stirring straws or longer drinking straws may be used with their free end in air or immersed in water for increased resistance.[4,17]

Despite the fact that tubes have been used in voice therapy since the 1960s,[1,17] their direct physiological and acoustical effect still remains an important topic in voice science. The tube's characteristics will determine the physical effects of these exercises on the phonation process. Therefore, selecting an appropriate tube according to specific patient needs can save time and resources and provide a more significant result.[3] Ideally, a well-chosen tube would have the same type of resistance as that provided by the glottal impedance.[18]

Variations in tube wall roughness, length, and inner diameter, as well as different free-end conditions during exercise execution (tube with its free end in air or immersed in water) will drastically modify the tube's flow resistance, the total pressure drop (back pressure) and, ultimately, the mechanisms associated with the effects on the voice, as observed in patients.[4,5,7] Although clinical studies have been successful at addressing the effectiveness of SOVTEs on improving voice parameters, they lack substantial information on how these improvements are achieved from a physical point of view. Furthermore, studies that address the influence of geometric properties of the tube on the flow resistance are still sparse in the literature.

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From the *Laboratory of Vibration and Acoustics, Federal University of Santa Catarina, Florianópolis, Brazil; and the †Department of Speech-Language Pathology and Audiology, Federal University of Santa Catarina, Florianópolis, Brazil.

Address correspondence and reprint requests to Andrey R. da Silva, Laboratory of Vibration and Acoustics, Federal University of Santa Catarina, Florianópolis, Brazil. E-mail: andrey.rs@ufsc.br

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The total flow resistance R is defined as the ratio between the total back pressure in the patient's mouth p_{back} and the volume flow U conveyed by the tube, which will mainly depend on the tube's geometry, particularly its length and inner diameter. Recent studies have shown that the tube's diameter plays a more decisive role than its length in flow resistance.[18,19] In addition, submerging the tube's free end in water creates another static component for the flow resistance, which helps to augment the back pressure.[4,5,18,19] Moreover, when the free end is immersed in water, the interplay between static pressure, buoyancy forces, and superficial tension creates a pulsating component of the back pressure due to bubble formation and shedding at the immersed end. As a consequence, the pulsating component will affect the vertical position of the larynx, as well as the glottal area and the glottal cycle itself,[4,20,21] also providing the patient an important sensory feedback during the exercise.[4,20]

Attempts have been made to quantify the relationship between pressure and flow in tubes varying in diameter and length, with the purpose of determining the tube resistance as a function of these two parameters.[18,19] Andrade et al[19] conducted an experimental investigation to evaluate the influence of the inner diameter and tube length on the back pressure p_{back} for different tubes. The results showed that the back pressure is significantly more sensitive to changes in the tube's inner diameter rather than changes in its length. Furthermore, they observed that, for immersed tubes, the effect of the water column on the back pressure is nearly constant as a function of the volume flow U for large diameter tubes.

Smith and Titze[18] proposed a semi-empirical flow resistance model, initially based on a fundamental equation for confined flows. The model was adjusted by an optimization process to provide the best curve fit between analytical and experimental results obtained for different tube geometries. Despite its excellent agreement with the experimental data, the model proposed by Smith and Titze cannot provide a clear physical interpretation of the contribution of the tube's geometrical parameters on the back pressure and flow resistance. This comes from the fact that the model is based on nonphysical coefficients obtained by the optimization process. The use of nonphysical coefficients also implies that the accuracy of the model is limited to the range of geometries considered in the experimental study, on which the optimization was conducted.

The objective of this paper is to provide an analytical model based on physical parameters that describes the relationship between back pressure and flow resistance as functions of the geometrical properties that define tubes used in SOVTEs, considering the free end in air and immersed in water. The model is obtained from the exact Darcy-Weisbach equation from fluid dynamics and can be used by clinicians to determine the equivalence between different tubes in order to provide similar therapy results. Moreover, the model can be used to provide a consistent quantitative analysis of the contribution of each geometrical parameter on the back pressure and flow resistance for a wide range of geometrical parameters.

THEORETICAL BACKGROUND

Tubes that carry flow will always present pressure drops Δp_i downstream in the flow direction caused by different energy loss mechanisms. The major loss mechanism, known as viscous loss, is caused by the conversion of the flow's kinetic energy into heat, as a consequence of fluid viscosity. Another major energy loss mechanism is known as kinetic energy loss, which exists because of the conversion of linear kinetic energy of the flow into rotational kinetic energy expressed in terms of vorticity. In turn, vorticity can be induced by flow instability or forced by discontinuities in the flow path, such as area expansions or contractions and curvature.[22,23] For tubes with one of its free ends immersed in water, an additional pressure drop term must be considered.

In the case of tubes used in SOVTEs, the back pressure p_{back} measured in the patient's mouth is the summation of the pressure drops Δp_i that appear along the tube, caused by these mechanisms.

Viscous loss

The pressure drop due to the viscous loss along a circular tube of length L and diameter D is governed by the Darcy-Weisbach equation[22]:

$$\Delta p_{vis} = f_{DW} \frac{8\rho}{\pi^2} \frac{LU^2}{D^5}, \tag{1}$$

where ρ is the fluid density. f_{DW} is a nondimensional parameter known as the Darcy-Weisbach friction factor, which depends on the characteristics of the tube and the flow, such as inner diameter D, wall roughness, volume flow U, and the fluid's kinematic viscosity ν. Moreover, f_{DW} will also depend on whether the flow regime is laminar or turbulent. A measure of the flow regime is expressed by the Reynolds number, which for flow in a pipe with circular cross-section is given by:

$$Re = 4U/\pi D\nu. \tag{2}$$

For flow in a circular pipe, the internal viscous forces acting on the fluid are dominant and the regime is laminar as long as $\mathrm{Re} \leq 2300$. For $Re > 2300$, internal inertial forces begin to dominate and the transition to a turbulent regime begins. Considering the expected range of volume flow associated with human phonation (0−1 L/s[18]) and the range of tube diameters commonly used in SOVTEs (1.5−9 mm), the regime is turbulent in the majority of cases.[18] In the case of a turbulent flow, the Darcy-Wiesbach friction factor f_{DW} is given by the Colebrook-White resistance equation,[24] expressed as:

$$\frac{1}{\sqrt{f_{DW}}} = -1.93\log\left(\frac{1.9}{Re\sqrt{f_{DW}}}\right). \tag{3}$$

Equation 3 is implicit and the values of f_{DW} can only be estimated numerically. Many approximated explicit forms for Equation 3 have been proposed,[25−27] whose accuracies will essentially depend on the flow characteristics. The explicit form provided by Haaland[25] provides an error proportional to the Reynolds number, which assumes the maximum value of

0.4% at $Re = 40.000$. Nevertheless, the range of Reynolds number found in SOVTEs is significantly smaller, such that the error implicit in Haaland's approximation becomes negligible. For this reason, the Haaland approximation has been chosen in the present formulation and is given by:

$$f_{DW} = \left[1.8\log\left(\left(\frac{\epsilon/D}{3.7}\right)^{1.11} + 5.42\nu\frac{D}{U}\right)\right]^{-2}, \quad (4)$$

where ϵ is the averaged roughness of the tube's inner walls. For plastic or glass tubes, one must consider $\epsilon \approx 1.0 \times 10^{-5}$m.[28]

Kinetic energy loss

Abrupt discontinuities in the tube cross-section area produce an adverse pressure gradient within the viscous boundary layer between the flow and the wall. This pressure gradient causes flow separation from the tube wall and, consequently, vorticity.[22] These phenomena force the transfer of translational to rotational kinetic energy and, ultimately, cause pressure drop. The expression for the kinematic pressure drop is given by:

$$\Delta p_{kin} = \frac{8\rho U^2}{\pi^2 D^4}(k_1 + k_2), \quad (5)$$

where k_1 and k_2 are loss coefficients associated with the discontinuities at the tube's open ends. Empirical values for k_1 and k_2 can be found in different fluid engineering handbooks.[28,29] For the tube's end inserted into the patient's mouth, the geometric condition approximates that of a sudden area contraction, considering the cross-section areas of the oral cavity and the tube. In this case, the loss coefficient k_1 is given by[28]:

$$k_1 = 0.5\left[1 - \left(\frac{D}{D_m}\right)^2\right]^2, \quad (6)$$

where D and D_m are the tube's inner diameter and the effective diameter of the patient's oral cavity, respectively. It should be noted from Equation 6 that the exact value of k_1 will vary between 0.4 and 0.5, depending on the ratio D/D_m. The lower limit corresponds to a critical situation where the tube diameter is large ($D = 9$ mm) and the effective diameter of the oral cavity is very small ($D_m = 27$ mm). For situations different from this, the ratio D/D_m decreases and k_1 approximates to 0.5 asymptotically.

For the other tube end terminated in air, $k_2 \approx 1$. For the cases where the open end of the tube is immersed in water, the loss coefficient increases to $k_2 \approx 3$, but the exact value will depend on the insertion angle of the tube into the water.

The total loss coefficient k can be obtained by the summation of the two coefficients k_1 and k_2, as given in Equation 5. It is worth mentioning that another loss coefficient should be considered in the summation within Equation 5, in order to represent the effect of tube curvature, which may exist when silicone tubes are used for SOVTEs. Nevertheless, the loss coefficients normally found for smooth curvatures are significantly smaller than those found for the geometric conditions described above.[28,29] For this reason, the effect of curvature is neglected in this work.

Loss due to water column

The pressure drop caused by the water column, for the case of the immersed tube end, is characterized by the interplay of inertia and buoyancy forces and can exhibit diverse behaviors depending on the flow velocity. For relatively low Reynolds numbers ($Re < 50.000$), the pressure drop is dominated by a static pressure necessary to "push" the effective water column downstream.[30–32] This condition has been studied experimentally by Wistbacka et al[4] who observed that the pressure drop will depend mainly on water depth rather than volume flow U. As suggested by Wistbacka et al,[4] the pressure drop due to the presence of a water column can be expressed as:

$$\Delta p_{wc} = \rho_w g h, \quad (7)$$

where ρ_w is the water's density ($1 \cdot 10^3$ kg/m^3), g is the acceleration of gravity at sea level (9.81 m/s^2), and h is the water column height (m).

Flow resistance

The back pressure p_{back} in the patient's mouth necessary to convey a certain volume flow U through the tube can be obtained by the summation of the different pressure drops given by Equations 1, 5, and 7:

$$p_{back} = U^2\frac{8\rho}{\pi^2}\left[f_{DW}\frac{L}{D^5} + \frac{k}{D^4}\right] + \rho_w g h, \quad (8)$$

where k is the sum of the loss coefficients at the two terminations of the tube, as discussed in the section "Kinetic energy loss. From Equation 8, it is possible to derive an expression for the flow resistance, which is the ratio between the pressure drop Δp_T (back pressure) and volume flow U, given by:

$$R = U\frac{8\rho}{\pi^2}\left[f_{DW}\frac{L}{D^5} + \frac{k}{D^4}\right] + \frac{\rho_w g h}{U}. \quad (9)$$

A brief analysis of Equation 9 provides an interesting insight on the contribution of each pressure drop term on the flow resistance. The last term on the right-hand side represents the effect of the water column and is by far the most significant term for the flow resistance. It simply acts as an offset value, which is inversely proportional to the volume flow U. When the tube is not immersed in water, $h = 0$ and this term becomes zero.

The first term on the right-hand side represents contributions of both the viscous loss (first term within brackets) and the loss of translational kinetic energy (second term within brackets). Considering that f_{DW} and k have the same order of magnitude, the viscous term is expected to have a greater contribution than the kinetic energy term, particularly for long tube lengths L. This implies that the geometric conditions at the patient's mouth, which will define the loss coefficient k_1 at one of the tube's ends, will not play a significant role in the flow resistance, provided that the tube's length is at least one order of magnitude greater than its diameter. This is in line with the experimental results of Smith and Titze,[18] who did not find a significant effect of mouth configuration in terms of volume on the back pressure.

RESULTS AND DISCUSSION

Tubes terminated by air

Figure 1 shows the results obtained for the back pressure p_{back} as a function of the volume flow U using Equation 8. The results are compared with both experimental and theoretical data obtained by Smith and Titze[18] for different tube lengths and diameters.

The analytical results provided by Equation 8 agree very well with the experiments, particularly for tubes longer than 6 cm and with diameters greater than 4.1 mm. This trend is also observed comparing the analytical results with the results given by the semi-empirical model of Smith and Titze and their experimental data. In general, the analytical model given by Equation 8 slightly underestimates the back pressure p_{back}, which becomes more pronounced as the tubes become shorter and thinner. For these cases, the maximum difference between analytical and experimental results is observed for the tube with $L = 3$ cm and $D = 2$ mm, which corresponds to $\approx$5%.

The increasing difference between analytical and experimental results for short and thin tubes is a consequence of two characteristics. First, Equation 8 was derived under the assumption that the flow regime within the tube is turbulent. However, the Reynolds number decreases significantly with the tube diameter and, for very thin tubes, the flow regime is a transition between laminar and turbulent flow, particularly for small volume flows U. This transition regime could have been taken into account in Equation 8. Nevertheless, the resulting analytical model would become significantly more intricate, which would hinder its practical application. The second reason for the deviation is associated with the tube length. For short tubes, kinetic energy losses become more pronounced than viscous losses. In this case, the uncertainty associated with the mouth's effective diameter D_m described in Equation 6 may induce a significant error.

It should be noted that exercises involving very thin and short pipes are less common than those involving long and wide-diameter tubes.[12] Nevertheless, for those cases involving thin and short tubes, the $\approx$5% error in the solution provided by Equation 8 is acceptable for practical applications.

Tubes terminated in water

Figure 2 depicts the results for a tube with $D = 9$ mm and $L = 36$ cm immersed in water at different water column depths. The results are compared with the experimental data provided by Andrade et al[19] and Wistbacka et al,[4] as well as with the results from the semi-empirical model by Smith and Titze[18] modified by Wistbacka et al[4] to take into account the effect of the water column.

In general, a very good agreement is found between the results obtained by Equation 8 and those obtained experimentally or by the semi-empirical model by Smith and Titze,[18] particularly for small water column depths. For higher water depths ($h > 4$ cm), the analytical results provided by Equation 8 show a better agreement with the experimental results provided by Andrade et al,[19] whereas the modified semi-empirical model by Smith and Titze shows a better agreement with the

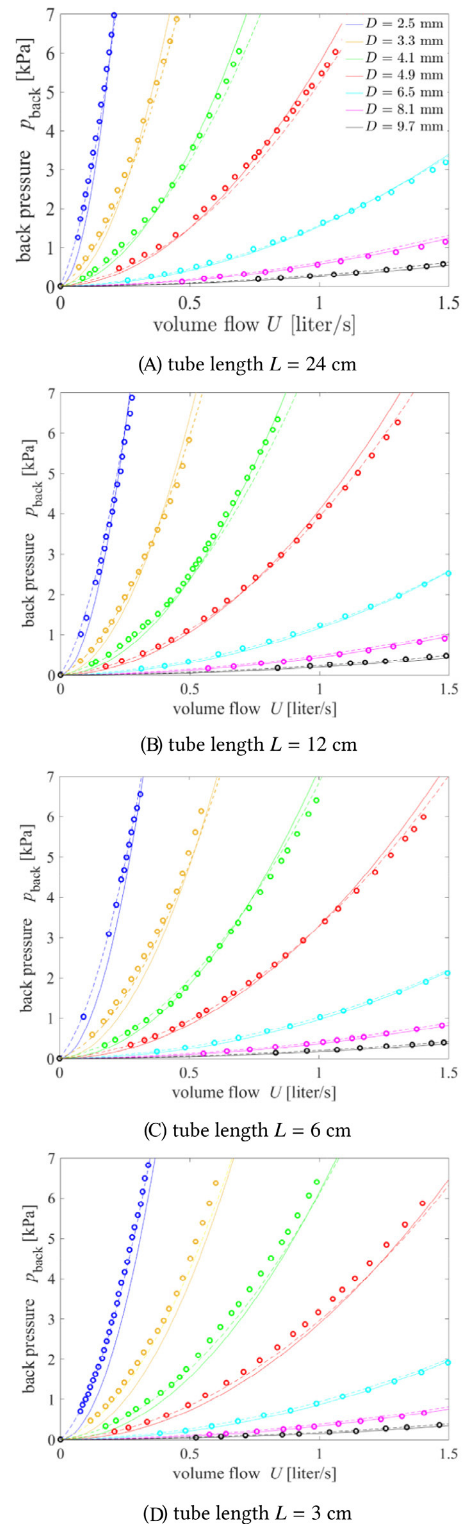

FIGURE 1. Total pressure drop (back pressure) p_{back} as a function of volume flow U for different tube geometries and the free end terminated in air. Circles correspond to the experimental results obtained by Smith and Titze,[18] dashed curves correspond to values obtained with the semi-empirical model by Smith and Titze,[18] and the continuous curves correspond to the analytical solution obtained with Equation 8. Colors indicate different tube diameters. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

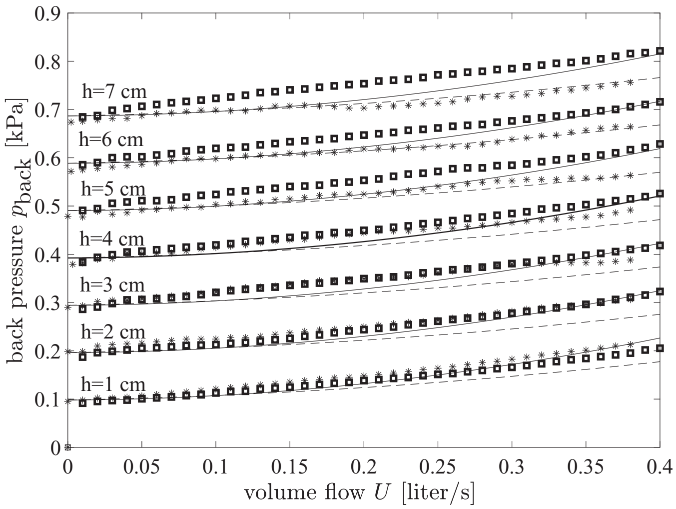

FIGURE 2. Back pressure p_{back} as a function of volume flow U for a tube with $D = 9$ mm and $L = 36$ cm with the free end terminated in water at different water column heights. Solid lines correspond to the analytical solution provided by Equation 8, dashed lines correspond to the solution of the semi-empirical model by Smith and Titze,[18] adapted by Wistbacka et al.[4] for the effect of the water column. *Squares* (□) correspond to the experimental results by Andrade et al.[19] and *asterisks* (*) correspond to the experimental results by Wistbacka et al.[4]

experimental results by Wistbacka et al.[4] The reason for these deviations are not clear. Nevertheless, it is interesting to note how the experimental results diverge from each other, particularly at higher water depths. This deviation might be related with experimental uncertainties associated with the angle of the immersed tube, as it might play an important role on the buoyancy forces related to bubble shedding.[30,31]

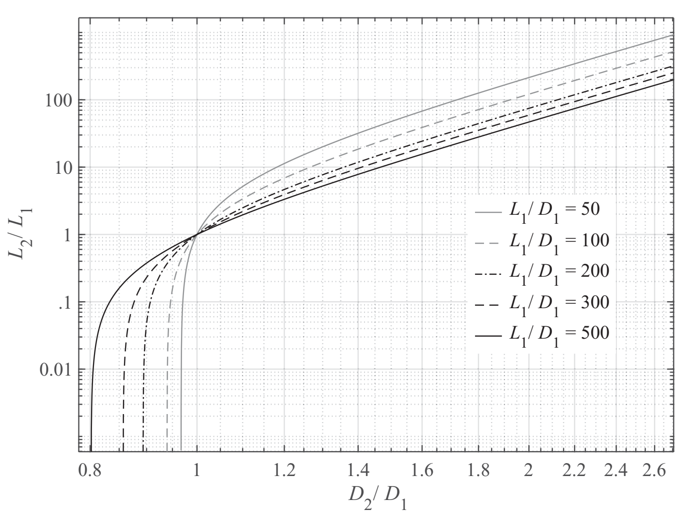

FIGURE 3. Isometric resistance chart. L_1, D_1 are the length (mm) and diameter (mm) of the reference, respectively. Likewise, L_2, D_2 are the length (mm) and diameter (mm) of the equivalent tube, respectively.

Resistance charts

A simple, yet useful approach to using Equation 9 consists in deriving an isometric resistance chart as depicted in Figure 3. The purpose of the chart is to indicate the dimensions of an equivalent tube, so as to provide the same flow resistance produced by a reference tube, whose dimensions in terms of inner diameter D_1 and length L_1 are known. To obtain an equivalent tube, it is first necessary to define either the equivalent tube's length L_2 or its diameter D_2. The chart assumes that both reference and equivalent tubes have equivalent wall roughnesses. This is a plausible assumption, provided that either of the tubes are made with plastic, silicone, or glass.[28,29]

For instance, assuming a reference tube to have $L_1 = 250$ mm and $D_1 = 5$ mm, one wants to find the necessary length L_2 of an equivalent tube of diameter $D_2 = 8$ mm as to provide the same flow resistance given by the reference tube. In this case, the ratio between equivalent and reference diameters would be $D_2/D_1 = 1.6$ and the ratio between length L_1 and diameter D_1 of the reference tube would be 50. For those values, the chart would give the length ratio $L_2/L_1 = 70$, which implies that the length of the equivalent tube L_2 would have to be $250\,\text{mm}\cdot 70 = 17.5$ m in order to produce the same flow resistance provided by the reference tube.

The most important aspect of the chart is that it can be easily used by professionals to assess the dimensions of equivalent tubes, provided that the length and diameter of a reference tube are known. Furthermore, from the theoretical viewpoint, the chart provides a quantitative measure on how flow resistance is significantly more sensitive to the inner diameter, rather than the tube's length. These findings agree with previous experimental observations by Andrade et al.[19] In other words, it can be seen that very small variations on the tube diameter require huge variations on the tube's length to maintain the same flow resistance. This is an important reminder for clinicians, as arbitrary tubes should not be expected to provide the same flow resistance as a reference tube, unless the exact relationship between inner diameter and length provided by the chart is used.

The chart has been plotted from Equation 9, assuming the volume flow U to be constant and equal to 0.4 L/s. Nevertheless, using greater values of volume flow up to 1 L/s provided a similar behavior of the curves, with a slight variation of less than 1%.

CONCLUSIONS

An analytical model for the relationship between flow resistance and geometric properties of tubes used in SOVTEs has been presented. The results obtained from the model agreed very well with both experimental and theoretical results provided by the literature, considering different geometries and free-end conditions (tubes with the free end in air or immersed in water).

The analysis of the model showed that the flow resistance is significantly more sensitive to variations on the inner diameter than to the tube's length, which agrees with previous experimental results.[18,19] Moreover, it has been shown that the viscous losses are much more significant than kinetic energy losses for tubes whose length are at least one order of magnitude greater than the inner diameter. For those cases, the effect of the mouth configuration is negligible. Nevertheless, for short tubes ($L/D < 10$) the mouth configuration becomes significant, and the flow resistance will be governed mainly by the ratio between the tube's inner diameter and the effective diameter of the patient's mouth.

The model was used to construct an isometric resistance chart, which can be used to indicate the dimensions of an equivalent tube, which would provide the same flow resistance produced by a reference tube, whose dimensions in terms of inner diameter D_1 and length L_1 are known. The chart is a useful tool for clinicians when selecting appropriate tubes for SOVTEs with specific therapeutic purposes or different patient needs.

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