AIRFLOW RESISTANCE OF AIRFLOW-REGULATING DEVICES DESCRIBED BY INDEPENDENT COEFFICIENTS

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Rehabilitation after laryngectomy includes more and more the use of airflow-regulating devices such as shunt valves (SVs), tracheostoma valves (TSVs), and heat and moisture exchange (HME) filters. In determining the quality of those devices, airflow resistance is a very important factor. It is currently defined as pressure drop divided by airflow. However, for most applications, this definition does not result in a pressure- and airflow-independent parameter. Therefore, a new set of parameters is defined and applied to pressure-airflow curves of airflow-regulating devices. Pressure drop over TSVs and HME filters appears to have a squared relationship with flow. In SVs, it has a linear relationship. The new set of parameters describes the pressure-airflow relationship properly for all considered devices. In conclusion, theoretical predictions of flow mechanics appear to be valid for SVs, TSVs, and HME filters. Only 2 coefficients are necessary to describe the pressure-flow characteristics of these airflow-regulating devices, independent of pressure drop over and flow through the device.

KEY WORDS — airflow resistance, heat and moisture exchange filter, laryngectomy, pressure drop, shunt valve, tracheostoma valve.

INTRODUCTION

The treatment of a malignant tumor in the laryngeal area often consists of surgical removal of the larynx (laryngectomy), including the vocal folds and epiglottis. Reconstruction results in separation of the airway and digestive tract (Fig 1). The trachea is led outside and ends in a tracheostoma. During the operation, a fistula is created between the trachea and esophagus. In the fistula, a shunt valve is placed.1 The shunt valve prevents food and fluid from entering the trachea and allows airflow from the trachea to the esophagus. Speech is made possible by closing the tracheostoma manually; expired air then flows via the shunt valve through the upper esophageal sphincter, which starts to vibrate and serves as a substitute for the vocal folds (pseudoglottis). Several types of shunt valve are available on the market, such as the Provox2 and the Groningen button,3 which are used regularly in spite of their limited lifetime.4,5

When the skin around the tracheostoma is sufficiently flat, a tracheostoma valve can be used.6-11 It is glued onto the skin around the tracheostoma. Hands-free speech is made possible by producing a spurt of air that closes the tracheostoma valve. To improve the rehabilitation process, a heat and moisture exchange (HME) filter can be applied. It moisturizes and warms the inhaled air12,13 to prevent the tracheal tissues from drying out, and thus reduces excessive mucus production and the occurrence of crusts in the trachea. Also, by raising airflow resistance, the HME filter increases the tissue oxygen saturation.14 An HME filter can be attached to a tracheostoma valve or applied independently by gluing it onto the skin like a tracheostoma valve.

An aspect common to all the devices mentioned above is airflow regulation. During airflow passage, they regulate the humidity and temperature (HME filters) or regulate the direction of the airflow (tracheostoma valve, shunt valve). One of the factors that determines the quality of these airflow-regulating...
devices is the pressure drop over the device. Devices with a high pressure drop require a high pressure to produce a certain airflow; thus, much energy is needed for the patient to inhale and exhale. When realization of these high pressures is not possible, a limited airflow will result, which might cause problems in breathing. Pressure drop depends strongly on airflow, so a more independent parameter, airflow resistance, is used to quantitate it.5,15-18

Airflow resistance is often defined as the pressure drop over the device divided by the airflow through the device, analogous to the electrical resistance of an electrical device, which is defined as the voltage drop over the device divided by the direct current through the device. Electrical resistance defined in this way appears to be a constant. That is, an increased voltage results in an increased current such that the quotient of voltage and current remains unchanged; thus, electrical resistance is independent of voltage and current. Electrical resistance is therefore an appropriate parameter for describing electrical behavior.

However, airflow resistance is a more complex phenomenon. Obtaining an independent parameter for airflow resistance by simply dividing pressure drop by airflow does not automatically result in a constant that is valid for all possible airflow and pressure values. A correct interpretation of a given flow resistance value is only possible in combination with flow values, but often, this combination is lacking, as in the articles of Cole et al,19 McRae et al,20 and Smithieran and Hixon.21

The aim of this article is to provide more insight into airflow behavior and description and to define a set of parameters that is appropriate for describing the airflow resistance of airflow-regulating devices for patients who have undergone laryngectomy. For each type of device (tracheostoma valves, HME filters, and shunt valves), the most appropriate parameter was derived and checked for its independence by use of existing information about pressure-flow relationships.

**MATERIALS AND METHODS**

Recently, extensive studies on the airflow and pressure characteristics of airflow-regulating devices have been performed.22-25 Four tracheostoma valves have been analyzed: the Blom-Singer ATV (Adjustable Tracheostoma Valve, Inhealth Technologies, Carpi- teria, California); the Bivona I and the Bivona II tracheostoma valves (Bivona Medical Technologies, Gary, Indiana); and the Adeva Window (Adeva Medical, Lübeck, Germany). Four HME filters have been analyzed: the Blom-Singer HumidiFilter (Inhealth Technologies); the Provox stoma filter (Atos Medical AB, Hörby, Sweden); the Free Vent (Pharma Systems AB, Knivsta, Sweden); and the Stom-Vent 2 (Louis Gibeck AB, Upplands Väsby, Sweden). Five shunt valves have been analyzed: the Blom-Singer indwell- ing low-pressure voice prosthesis (Gelcap, Inhealth Technologies); the Groningen Ultra Low Resistance (Medin Instruments, Groningen, the Netherlands); the Provox and the Provox-2 (Atos Medical AB); and the VoiceMaster (Entermed, Woerden, the Netherlands).

Figures 2-422-25 show the relationships between the pressure loss and flow of the analyzed tracheostoma valves, HME filters, and shunt valves, respectively. Data derived from these graphs will be used in this discussion.

For each type of device, a numerical description of the relationship between airflow through the device and pressure drop over the device will be made.
The numerical description will be used to define a parameter that is independent of airflow and pressure drop. For each device, the value of this parameter will be calculated from the data in Figs 2-4. A graph of the parameter values plotted against the airflow will demonstrate whether the parameter is indeed independent of airflow and pressure drop. In general, the simplest way to describe the relationship between pressure drop and airflow is given by the modified Bernoulli equation:

\[ \Delta P = \frac{1}{2} \rho \cdot v^2 \cdot (\lambda \cdot \frac{L}{d} + K) \]

where:
- \( \Delta P \) = pressure drop over the considered region [Pa]
- \( \rho \) = air density [kg/m³]
- \( v \) = mean airflow velocity = \( 4 \cdot \frac{Q}{\pi \cdot d^2} \) [m/s]
- \( Q \) = airflow [m³/s]
- \( \lambda \) = airflow resistance factor
- \( \lambda = \frac{64}{Re} \) when the airflow is linear (Re < 2,300); \( \lambda = \frac{0.316}{Re^{0.25}} \) when the airflow is turbulent (Re > 2,300)
- \( Re = \frac{\rho \cdot v \cdot d}{\eta} \)
- \( \eta \) = dynamic airflow viscosity [Pa • s]
- \( L \) = length of the considered region [m]
- \( K \) = airflow resistance factor, caused by a change in diameter from \( D \) to \( d \) (\( D > d \)) = \( \left(1 - \frac{d^2}{D^2}\right)^2 \)

Some assumptions are included in this equation:
1. Airflow viscosity is constant (= 17.1 • 10⁻⁶ Pa • s).
2. Air density is constant (= 1.29 kg/m³).
3. Pressure is constant in a plane perpendicular to the streamline.

For shunt valves, we have to consider an additional pressure drop caused by the elastic deformation of the valve. The pressure that is necessary to deform the valve in order to open it can be described by Hooke’s law. This implies a linear relationship between pressure drop and airflow:

\[ \Delta P = c \cdot Q \]

For shunt valves, formula 1 becomes:

\[ \Delta P = \frac{1}{2} \rho \cdot v^2 \cdot (\lambda \cdot \frac{L}{d} + K) + c \cdot Q \]

with \( c \) = elastic constant, depending on valve size and material [Pa • s/m³]. When all constant factors are integrated, formula 2 becomes

\[ \Delta P = ARC_1 \cdot Q + ARC_2 \cdot Q^2 + ARC_3 \cdot Q^{1.75} \]

with
- \( ARC_1 \) = airflow resistance coefficient caused by wall friction of a laminar airflow or by deformation of a valve
- \( ARC_2 \) = airflow resistance coefficient caused by a
change in diameter

- ARC3 = turbulent airflow resistance coefficient caused by wall friction

These 3 potential airflow resistance parameters will be used to describe the airflow behavior of the considered devices.

RESULTS

For tracheostoma valves, formula 2 can only be dominated by wall friction or by friction caused by a change in diameter (the trachea has an internal diameter of about 25 mm, and the internal lumen of the tracheostoma valve has a smaller diameter), since there is no active valve present (c = 0). When the internal lumen of a tracheostoma valve is assumed to be circular with a diameter of 10 mm and a shaft length of 20 mm, then according to formula 2, the pressure drop of a change in diameter is 73.9 Pa, which is more than 10 times higher than the pressure drop caused by wall friction (6.7 Pa). The resulting total pressure drop (80.5 Pa at a flow of 1 L/s) resembles that of Fig 2, so the numerical calculation seems to be correct. Therefore, airflow resistance is best described by ARC2. In Fig 5,23,24 pressure drop is plotted against the squared airflow values by use of data in Fig 2. Good linear relationships, and thus, rather constant ARC2 values, result. Table 1 presents the ARC2 values of the considered tracheostoma valves for these airflow.

The airflow resistance of HME filters is likewise dominated by wall friction or by friction caused by a change in diameter. Wall friction is caused by an airflow that comes into contact with the walls of the little canals in the foam. A change in diameter is caused by the fact that the total cross-sectional area of an HME filter through which air can flow (the summation of all the little canals) is much smaller than the cross-sectional area of the trachea. To analyze which cause is dominant, the flow behavior of the foam is modeled by considering a composition of numerous little canals placed parallel to each other. The length of a canal is considered to be twice the foam thickness, simulating its capricious orientation. By adding the internal surfaces of all canals, the diameter of an imaginary lumen with the same surface can be calculated. This lumen diameter is used to estimate the dominant cause of friction.

When assuming an internal canal diameter of 1 mm, the pressure drop calculated with formula 2 is 132.4 Pa, which resembles the pressures of Fig 3, thus validating the model. It appears that the pressure

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TABLE 1. ARC2 OF TRACHEOSTOMA VALVES FOR FOUR VALVE POSITIONS DERIVED FROM DATA IN FIGURE 2

<table>
<thead>
<tr>
<th>Tracheostoma Valve and Position</th>
<th>ARC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bivona I-f</td>
<td>39</td>
</tr>
<tr>
<td>Bivona I-m</td>
<td>35</td>
</tr>
<tr>
<td>Bivona I-l</td>
<td>38</td>
</tr>
<tr>
<td>Bivona I-u</td>
<td>29</td>
</tr>
<tr>
<td>ATV-0</td>
<td>43</td>
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<tr>
<td>ATV-0</td>
<td>60</td>
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<tr>
<td>ATV-30</td>
<td>67</td>
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<tr>
<td>ATV-60</td>
<td>122</td>
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<tr>
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<td>260</td>
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<tr>
<td>Bivona II-30</td>
<td>139</td>
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<td>146</td>
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<td>140</td>
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<tr>
<td>Bivona II-15</td>
<td>136</td>
</tr>
<tr>
<td>Adeva Window</td>
<td>110</td>
</tr>
</tbody>
</table>

ARC2 is in Pa • s²/L². Data from Fig 2B are in italics. Valve positions are indicated by f, m, l, u for Bivona I; 0, 30, 60, 90 for ATV; and 30, 25, 20, 15 for Bivona II.
drop caused by a change in diameter (from tracheal size to the imaginary lumen) is 131.3 Pa, which is more than 100 times higher than the pressure drop caused by friction (1.1 Pa), so again, airflow resistance is best described by ARC2. In Fig 6, pressure drop is plotted against squared airflow by use of the data in Fig 3. When the data of Grolman et al are used, no linear relationship appears. However, using the data of Verkerke et al results in the expected linear relationship. The ARC2 values that are presented in Table 2 are based on the data of Verkerke et al.

In shunt valves, formula 2 can be dominated by all 3 elements: wall friction, friction caused by a change in diameter (the trachea has an internal diameter of about 25 mm, and the internal lumen of the shunt valve is narrower), and elastic deformation of the valve. Most shunt valves can be characterized by an internal diameter of 5 mm and a shaft length of 10 mm. By use of these dimensions, the change in diameter appears responsible for 138.9 Pa, which is 9% of the total pressure drop mentioned in Fig 4, and wall friction is responsible for 10.9 Pa, which is 1% of the total pressure drop, so valve deformation will dominate the total airflow resistance. Airflow resistance is therefore best described by ARC1.

Figure 4 shows that for 3 of the 5 shunt valve types, nearly linear relationships exist. Table 3 presents the ARC1 values. The Provox and Provox-2 show a linear behavior only at certain flow intervals (Fig 7): for the Provox-2, >0.05 L/s, and for the Provox, <0.25 L/s. The ARC1 values of Table 3 are only valid for these flows.

**DISCUSSION**

Airflow-regulating devices are essential in today’s rehabilitation of patients who have undergone laryngectomy. The airflow resistance of these devices is a very important characteristic. The lower the airflow resistance is, the higher the comfort for the patient will be. Before airflow resistance can be decreased by changing the design of the device and in order to compare the different devices or models, airflow resistance must be understood and described by pressure- and flow-independent parameters.

Wheatley et al described the 3 possible relationships between pressure drop and airflow, but only considered their separate appearance, not their simultaneous appearance. Rohrer’s equation considers only 2 possible relationships: a linear one and a quadratic one.

The presented formula 2 clearly describes total airflow behavior for all the considered airflow-regulating devices. However, in general, each formula is a simplification of reality. In the formula presented,
airflow viscosity and air density are considered to be constant. Air viscosity depends mainly on temperature, which remains constant within small margins. Air can be considered incompressible for air velocities up to 70 m/s, a limit that is not reached in this study, because the air velocities in the presented devices calculated with formula 1 are 18 m/s at the highest. The assumption that pressure is constant in a plane perpendicular to the streamline is acceptable for the considered geometry.26

The data for tracheostoma valves in Fig 5 show that the assumed relationship between airflow and pressure drop exists, especially for flows of 0.5 L/s and higher, so pressure drop is indeed caused by a change in diameter. Wall friction is less important, because the air velocity is relatively low and the length of tracheostoma valves is short. Figure 5 and Table 1 show that a large variation in airflow resistance exists. From formula 2 can be derived that airflow resistance decreases up to 16 times when the lumen diameter is doubled. So, the large variation in airflow resistance is, most probably, caused by small variations in lumen diameter.

When we use the data of Grolman et al,24 HME filters do not behave as expected. However, the measurements were performed at only 3 different airflows, so it is difficult to draw distinct conclusions. Using the data of Verkerke et al,23 who included a greater number of different airflows, resulted in the expected constant ARC2 values. When we compare the results in both publications, we find the data of Verkerke et al to be up to 2 times higher. The reason for this difference cannot be explained.

Shunt valves generally show, indeed, the expected behavior, so the assumed dominance of elastic valve deformation in the airflow resistance exists. However, the 2 Provox devices show a somewhat different behavior. First, high opening pressures exist, probably because the valves stick to the housing. Second, the relationship between pressure and flow is not linear, but has a quadratic component. This is most probably because the inner diameter is restricted in comparison to that of other shunt valves, and because the valve has a small hinge that requires less elastic deformation during valve opening. According to formula 1, the contribution to the total friction of wall friction and friction caused by a change in diameter will rise from 10% to 25%, thus explaining the more quadratic behavior. The range in which rather constant ARC2 values exists is from 0.05 to 0.25 L/s, which falls within the physiological range. Since no device is dominated by wall friction, ARC3 is not necessary for describing airflow resistance, and 2 parameters, ARC1 and ARC2, are sufficient.

CONCLUSION

A practical set of 2 coefficients (ARC1 and ARC2) has been defined to describe airflow resistance. The advantage of these coefficients is that they are independent of airflow and pressure. Comparing devices can be performed by comparing the coefficient values instead of comparing pressure-flow diagrams. ARC1 is defined by pressure divided by flow; ARC2 is defined by pressure divided by squared flow. It appeared possible to characterize shunt valves (except Provox) by ARC1 and tracheostoma valves and HME filters by ARC2. Because, for each device type, the main cause of airflow resistance has been analyzed, an efficient improvement of existing devices or designing of new devices becomes possible.

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