Interaction of cross-sectional area, driving pressure, and airflow of passive velopharynx

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Interaction of cross-sectional area, driving pressure, and airflow of passive velopharynx. J. Appl. Physiol. 83(3): 851–859, 1997.—Previous studies have shown that, when the pharyngeal muscles are relaxed, the velopharynx is a highly compliant segment of the pharynx. Thus, under these circumstances, cross-sectional area of the velopharynx (A<sub>vp</sub>), driving pressure across the velopharynx (ΔP), and inspiratory airflow (V<sub>i</sub>) will be mutually interdependent variables. The purpose of the present investigation was to describe the interrelation among these three variables during inspiration. We studied 15 sleeping patients with obstructive sleep apnea/hypopnea when the pharyngeal muscles were rendered hypotonic by applying continuous positive airway pressure to the nasal airway. A<sub>vp</sub>, determined by endoscopic imaging, was significantly greater at onset of V<sub>i</sub> limitation than at minimum oropharyngeal pressure (P<sub>0.1</sub>) (5). Snoring was never observed during V<sub>i</sub> limitation. In this way, a highly compliant velopharynx contributes to an increase in oropharyngeal pressure that, in turn, counterbalances the decrease in ΔP during flow limitation.

obstructive sleep apnea; pharyngeal mechanics; fluid flow dynamics; flow limitation; dynamic collapse

MATERIALS AND METHODS

Subjects. We studied 15 patients who had documented OSA and had a site of primary narrowing only at the velopharynx. Static characteristics of the velopharynx in patients 7–15 were previously reported (8). Mean values ± SD for age and body mass index were 42.3 ± 13.1 yr and 31.1 ± 6.1 kg/m<sup>2</sup>, respectively. Mean apnea/hypopnea index for the group was 40.5 ± 28.7/h as determined by standard full-night polysomnography (19). The purposes and potential risks of the study were fully explained, and written informed consent was obtained from all patients. The investigation was approved by the Research Ethics Review Board of the University of Calgary.

Experimental procedures. Experimental recording procedures have been described in detail in previous reports (8, 13, 15). An electroencephalogram (C4–A1), electrooculograms, and a submental electromyogram were continuously monitored together with arterial oxygen saturation (Biox 3700, Ohmeda) and tracheal sound (Oyster23, Schaller piezoelectric). After local anesthesia of the nasal passages was induced with 2 ml of 2% lidocaine, two side-hole, water-filled catheters (2-mm OD) connected to suitable pressure transducers (MX 860, Medex) were inserted through the naris. The tip of one catheter, positioned in the oropharynx, recorded oropharyngeal pressure (P<sub>op</sub>); the tip of the other, located high in the nasopharynx, recorded nasopharyngeal pressure (P<sub>np</sub>). We calculated driving pressure across the pharynx (ΔP), defined
as Pnp - Pop. The catheters were perfused by a slow, bias flow of water. A fiberoptic endoscope (PF-27L, 2.7-mm OD, Olympus) was inserted through the nose to visualize the pharynx. A nasal CPAP mask was applied to the patient and sealed to the skin by using a silicone rubber foam. Care was taken to eliminate leaks. The nose mask was connected to a pressure servocontroller through a pneumotachograph (Fleisch no. 1). The pressure servocontroller regulated nasal airway pressure with positive and negative blowers by using the mask pressure (Pm) as a feedback signal. Pm was measured by using a differential transducer (MP-45, Validyne). The polysomnographic data, pressure, and flow were recorded on a 16-channel recorder (ES 1000, Gould). The fiberscope was connected to a camera (WC-CD 50, Panasonic), and the image was displayed and recorded on a videotape, along with a time code (TS010, Telecom Research). The time code, together with simultaneously recorded values of pressure and flow, was stored in a personal computer. This dual recording of the time code allowed subsequent identification of pressure and flow values corresponding to the simultaneously recorded image.

The subject was allowed to fall asleep while lying supine, with the neck in a neutral position, and the study was performed during non-rapid-eye-movement sleep. In four cases, adequate data were obtained during natural sleep. In 11 cases, such data were not obtained because sleep was disrupted, and adequate sleep occurred only after intravenous injection of midazolam (10–15 mg). Pm was set at a level that fully distended the pharynx, as determined by progressive increase in Pm until no further increase in V˙I, as a primary or secondary site of narrowing, according to previous described criteria (13, 15). In all these cases, the site of nasopharyngeal closure was restricted to the velopharynx (end of nasal septum to margin of soft palate) were viewed. Each pharyngeal segment was classified as a primary or secondary site of narrowing, according to previously described criteria (13, 15). In all these cases, the site of nasopharyngeal closure was restricted to the velopharynx, the segment of the nasopharynx bounded ventrally by the soft palate.

The videotaped images corresponding to selected times (see Data analysis) were digitized (data translation DT2803, Frame Grabber). AVP in each image was measured by using cursor-controlled software, and the absolute value for AVP was calculated by reference to the diameter of the pressure catheter (1.7 or 2.0 mm) where it passed through the lumen of the constraining segment.

Accuracy of the pressure and AVP measurements. Response characteristics of the pressure measurement with the fluid-filled catheter were carefully evaluated by using a rigid container (25 liters) with a loudspeaker mounted in the wall. The speaker was driven by a sine wave to create a pressure wave in the container. Responses of the fluid-filled pressure catheter-transducer system with the bias-flow running water were compared with that of a high-frequency air-filled transducer (MP-45, Validyne). The amplitude of the pressure wave recorded by the fluid-filled catheter stayed constant ±5% up to 13 Hz. The time delay due to phase shift between fluid-filled catheter system and air-filled transducer was < 0.025 s up to 13 Hz. Sudden rupture of elastic membrane covering a rigid container was used to provide a square-wave pressure signal. A 90–10% and 10–90% response to ± 10 cmH2O square pressure signal was reached within 0.055 s.

Accuracy of the measurement of the AVP was validated by using various tubes of known cross-sectional area (range: 0.12–1.77 cm²) and found to be accurate within 10%.

Data analysis. As we previously reported, static velopharyngeal pressure/area relationships for each of the six subgroup patients was described by the exponential equation

\[ A_{VP} = A_{max} - B \cdot \exp(-C \cdot P_{il}) \]  (1)

where maximal area (Amax), B, and C are constants, and Pil denotes intraluminal pressure at the velopharynx (8). We calculated static velopharyngeal compliance (dA/dPil) for any value of AVP from the equation, dA/dPil = C \cdot (A_{max} - A_{VP}).

For each single-breath test having Pm greater than Pc, we examined the relation between Vi and ∆P. When no increase in airflow was observed, despite increasing ∆P, the inspiration was classified as flow limited. Conversely, when positive dependence of Vi on ∆P was observed, throughout the test inspiration, the inspiration was classified as non-flow-limited inspiration.

The mechanical behavior of the velopharynx during flow-limited inspiration was evaluated in four to five single-breath tests (mean = 4.5) in each of the 15 patients. Values of ∆P and AVP were obtained at the beginning of inspiration, and values of Vi, ∆P, and AVP were measured at the onset of flow limitation and at the nadir of Pop. A more detailed analysis of the behavior of the velopharynx was performed in a subgroup of six patients (patients 1–6). In these six patients, referred to as subgroup patients, values for ∆P, Vi, and AVP were collected every 0.1 s throughout inspiration for flow-limited and non-flow-limited inspirations. Resistance of the nose (Rn) and the velopharynx (Rvp) were calculated as the ratio of the driving pressure for each segment (Pm/Pnp or Pnp/Pop) to the simultaneously observed airflow.

Data derived from the subgroup of six patients were fitted with the following equation

\[ \dot{V}_i = K \cdot A_{VP} \cdot \Delta P^b \]  (2)

where K, a, and b are constants. Among the possible mathematical models, we chose Eq. 2 because we consider that 1) Vi increases as ∆P increases for a constant geometry; 2) large Vi is obtained by a constant ∆P as AVP increases; and 3) during flow limitation, increase in ∆P is balanced by simultaneous reduction of AVP. Individual patient data and group data were fitted to the equation by using a nonlinear, least-squares method (NONLIN SYSTAT, 1985). Because the values of a and b were nearly equal to unity and 0.33, respectively, we defined a variable impedance (Z) of the velopharynx, as follows

\[ Z = K^{-1/3} / A_{VP} = P^{0.33} \dot{V} \]  (3)

Although the definition of Z is derived from this simple mathematical arrangement, Z possibly has physiological meaning. Equation 3 indicates that Z inversely relates to changes in AVP, and describes ∆P-Vi relationship for a constant AVP. Therefore, Z reflects the resistive characteristics of the velopharynx when the air flows through it due to introduc-
tukey's test. analysis was performed by using analysis of variance and (pm

r

\( \text{R}_{\text{IO}} \), \( \text{R}_{\text{VP}} \), and \( Z \) for each of these three times for each of the 15 patients. mean \( \text{V}_{\text{i}} \) was greater at onset of flow limitation than at minimum \( \text{P}_{\text{op}} \) (\( P < 0.05 \)). compared with the value at beginning of inspiration, the mean value of \( \text{A}_{\text{VP}} \) was 30% less at the onset of flow limitation (\( P < 0.05 \)) and 66% less at the nadir in \( \text{P}_{\text{op}} \) (\( P < 0.01 \)). Mean values of \( \text{P}_{\text{ke}} \) increased significantly from onset of flow limitation to minimum \( \text{P}_{\text{op}} \) (\( P < 0.01 \)). Mean values of \( \text{R}_{\text{VP}} \) and \( Z \) increased significantly during flow limitation, whereas \( \text{R}_{\text{IN}} \) showed no change. figure 1

Table 2. Dynamic characteristics of velopharynx in group of 15 patients

<table>
<thead>
<tr>
<th>Site of Narrowing</th>
<th>Patients</th>
<th>Primary</th>
<th>Secondary</th>
<th>( \text{P}_{\text{h}} ) ( \text{cmH}_2\text{O} )</th>
<th>( \text{P}_{\text{c}} ) ( \text{cmH}_2\text{O} )</th>
<th>( \text{A}_{\text{VP}} ) at ( \text{Ph} ) ( \text{cm}^2 )</th>
<th>( \text{A}<em>{\text{VP}} - \text{A}</em>{\text{max}} ) - ( \text{B} \cdot \exp (- C \cdot \text{P}_{\text{op}}) )</th>
<th>( \text{A}_{\text{max}} )</th>
<th>B</th>
<th>C</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( \text{VP} )</td>
<td>( \text{HP} ), 68%</td>
<td>14.0</td>
<td>3.1</td>
<td>1.33</td>
<td>1.32</td>
<td>3.11</td>
<td>0.307</td>
<td>0.988</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 ( \text{VP} )</td>
<td>14.0</td>
<td>5.5</td>
<td>1.44</td>
<td>1.44</td>
<td>7.04</td>
<td>0.283</td>
<td>0.855</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 ( \text{VP} )</td>
<td>12.0</td>
<td>-1.0</td>
<td>1.55</td>
<td>1.74</td>
<td>1.48</td>
<td>0.310</td>
<td>0.990</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 ( \text{VP} )</td>
<td>7.0</td>
<td>-2.0</td>
<td>1.69</td>
<td>1.70</td>
<td>0.94</td>
<td>0.291</td>
<td>0.935</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 ( \text{VP} )</td>
<td>6.0</td>
<td>-3.9</td>
<td>1.34</td>
<td>1.35</td>
<td>0.50</td>
<td>0.255</td>
<td>0.946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 ( \text{VP} )</td>
<td>11.0</td>
<td>1.0</td>
<td>1.49</td>
<td>1.50</td>
<td>2.00</td>
<td>0.229</td>
<td>0.926</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 ( \text{VP} )</td>
<td>8.0</td>
<td>1.0</td>
<td>1.13</td>
<td>1.25</td>
<td>1.75</td>
<td>0.350</td>
<td>0.989</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 ( \text{VP} )</td>
<td>( \text{OP} ), 25%</td>
<td>12.0</td>
<td>1.0</td>
<td>2.21</td>
<td>2.28</td>
<td>3.21</td>
<td>0.364</td>
<td>0.990</td>
<td></td>
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<tr>
<td>9 ( \text{VP} )</td>
<td>( \text{OP} ), 30%</td>
<td>10.0</td>
<td>1.0</td>
<td>1.20</td>
<td>1.18</td>
<td>2.70</td>
<td>0.859</td>
<td>0.995</td>
<td></td>
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</tr>
<tr>
<td>10 ( \text{VP} )</td>
<td>( \text{OP} ), 37%</td>
<td>10.0</td>
<td>1.0</td>
<td>1.16</td>
<td>1.05</td>
<td>0.71</td>
<td>0.266</td>
<td>0.990</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 ( \text{VP} )</td>
<td>( \text{HP} ), 45%</td>
<td>7.0</td>
<td>0.7</td>
<td>1.01</td>
<td>1.14</td>
<td>1.46</td>
<td>0.274</td>
<td>0.970</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 ( \text{VP} )</td>
<td>( \text{HP} ), 36%</td>
<td>6.0</td>
<td>-0.7</td>
<td>1.09</td>
<td>1.15</td>
<td>0.78</td>
<td>0.411</td>
<td>0.938</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 ( \text{VP} )</td>
<td>( \text{HP} ), 36%</td>
<td>11.0</td>
<td>0.7</td>
<td>2.12</td>
<td>1.26</td>
<td>0.81</td>
<td>0.213</td>
<td>0.994</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 ( \text{VP} )</td>
<td>( \text{OP} ), 45%</td>
<td>10.0</td>
<td>1.0</td>
<td>1.67</td>
<td>1.58</td>
<td>4.81</td>
<td>1.104</td>
<td>0.950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 ( \text{VP} )</td>
<td>( \text{OP} ), 25%</td>
<td>12.0</td>
<td>1.0</td>
<td>1.42</td>
<td>1.41</td>
<td>1.98</td>
<td>0.357</td>
<td>0.990</td>
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</tr>
</tbody>
</table>

Mean ± SD

| \( 10.2 ± 2.5 \) | \( 0.4 ± 2.2 \) | \( 1.38 ± 0.32 \) | \( 1.42 ± 0.31 \) | \( 2.22 ± 1.78 \) | \( 0.385 ± 0.253 \) | \( 0.963 ± 0.039 \) |

\( \text{VP} \), velopharynx; \( \text{OP} \), oropharynx; \( \text{HP} \), hypopharynx; \( \text{Ph} \), holding pressure of continuous positive airway pressure; \( \text{P}_{\text{c}} \), closing pressure; \( \text{A}_{\text{VP}} \), \( \text{VP} \) cross-sectional area; \( \text{Op}, \text{OP}, \text{36}\% \) 10.0 1.0 1.15 1.15 2.58 0.310 0.990 |

\( \text{VP} \), velopharynx; \( \text{OP} \), oropharynx; \( \text{HP} \), hypopharynx; \( \text{Ph} \), holding pressure of continuous positive airway pressure; \( \text{P}_{\text{c}} \), closing pressure; \( \text{A}_{\text{VP}} \), \( \text{VP} \) cross-sectional area; \( \text{Op}, \text{OP}, \text{36}\% \) 10.0 1.0 1.15 1.15 2.58 0.310 0.990 |

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\( \text{VP} \), velopharynx; \( \text{OP} \), oropharynx; \( \text{HP} \), hypopharynx; \( \text{Ph} \), holding pressure of continuous positive airway pressure; \( \text{P}_{\text{c}} \), closing pressure; \( \text{A}_{\text{VP}} \), \( \text{VP} \) cross-sectional area; \( \text{Op}, \text{OP}, \text{36}\% \) 10.0 1.0 1.15 1.15 2.58 0.310 0.990 |
illustrates dependence of $\dot{V}_i$ and $A_{VP}$ at onset of flow limitation on $P_m$ for each of 15 patients. For each patient, $\dot{V}_i$ and $A_{VP}$ at onset of flow limitation increased as $P_m$ increased.

Subgroup analysis of flow-limited and non-flow-limited inspirations. The dynamic behavior of the velopharynx during flow-limited and non-flow-limited inspirations was studied in 49 single-breath tests (34 flow-limited tests; 15 non-flow-limited tests) in the six subgroup patients (patients 1–6), where values of $\dot{V}_i$, $A_{VP}$, and $\Delta P$ were obtained at 0.1-s intervals. Figure 2 illustrates for one patient (patient 5) the typical time courses of $\dot{V}_i$, $\Delta P$, $A_{VP}$, $P_{ke}$, and $R_{VP}$ at four different values of $P_m$. The far left column provides an example of an inspiration without flow limitation ($P_m = 6$ cmH$_2$O). $\dot{V}_i$ progressively increased during inspiration as a result of a progressive increase in $\Delta P$ so that $R_{VP}$ remained at a low and constant value. Cross-sectional area decreased only slightly and, therefore, $P_{ke}$ changed little. By contrast, when $P_m$ was somewhat lower ($P_m = 1$ cmH$_2$O), inspiratory airflow was limited (Fig. 2, second column from left). During this flow-limited inspiration, $\dot{V}_i$ remained relatively constant, while $\Delta P$ increased slightly, $A_{VP}$ progressively decreased, and $P_{ke}$ continuously increased. These changes in $A_{VP}$, $\Delta P$, and $P_{ke}$ became more prominent at lower values of $P_m$ (Fig. 2, right two columns). In addition, at the lowest value of $P_m$ ($P_m = -1$ cmH$_2$O) (Fig. 2, far right column) $R_{VP}$ increases dramatically during flow limitation, whereas $\dot{V}_i$ decreases progressively.

The data for all 49 inspirations for each of the six patients were fitted by Eq. 2, and Table 3 provides the results of this curve-fitting procedure for each patient. $R^2$ values ranged from 0.744 to 0.906 with a mean $R^2$ for the group equal to 0.855. Positive values of the constants $a$ and $b$ indicate that independent increases in $A_{VP}$ and $\Delta P$ were associated with increases in $\dot{V}_i$. The relationships between $A_{VP}$, $\Delta P$, and $\dot{V}_i$ during flow-limited and non-flow-limited inspirations can be graphically displayed on a three-dimensional plot. Figure 3
illustrates a typical plot in one patient (patient 1) for eight test inspirations. Each thick line represents an iso-Pm curve, i.e., the locus of simultaneously observed values of three variables during inspiration at a single value of Pm. The upper grid surface formed by continuous lines graphically illustrates the regression

\[ \dot{V}_I = 0.486 - A_{VP}^{0.948} \cdot \Delta P^{0.300} \]  

which was produced by fitting all data for this patient to Eq. 2 \((R^2 = 0.853)\). The iso-\(\Delta P\) contour lines on this surface show that \(\dot{V}_I\) increases monotonically with increasing values of \(A_{VP}\) for any constant \(\Delta P\). Similarly, \(\dot{V}_I\) increases as \(\Delta P\) increases for any constant \(A_{VP}\) as demonstrated by the iso-\(A_{VP}\) contour lines. Experimentally observed iso-Pm contour lines for this patient are located near or on the surface. Each iso-Pm line crosses the iso-\(A_{VP}\) and iso-\(\Delta P\) guidelines, indicating that \(A_{VP}\) decreases and \(\Delta P\) increases during inspiration.

The results for all 49 inspirations in all six patients can be graphically summarized after normalizing \(A_{VP}\) to \(A_{VP \max}\) as shown in Fig. 4. In Fig. 4A, each line represents simultaneous values of \(\dot{V}_I\), \(\Delta P\), and \(A_{VP / A_{VP \max}}\) during inspiration at a constant value of Pm. Each iso-Pm curve provides the observed points for a single test inspiration. An inspiration beginning from a high value of \(A_{VP / A_{VP \max}}\) (i.e., relatively high Pm) ascends a steep curve such that \(\dot{V}_I\) increases with little change in \(A_{VP / A_{VP \max}}\) or \(\Delta P\). By contrast, an inspiration beginning from a low \(A_{VP / A_{VP \max}}\) (i.e., relatively low Pm) ascends on the surface less steeply (i.e., \(\Delta P\) and \(A_{VP / A_{VP \max}}\) change greatly for a unit increase in \(\dot{V}_I\)). This trajectory becomes progressively flatter, and then \(\dot{V}_I\) actually declines as \(\Delta P\) increases and \(A_{VP / A_{VP \max}}\) decreases. The upper grid (continuous lines) shown in Fig. 4B was generated by fitting Eq. 2 to all data for all six patients, yielding the following relationship

\[ \dot{V}_I = 0.657\left( \frac{A_{VP}}{A_{VP \max}} \right) \cdot \Delta P^{0.332} \]  

\((R^2 = 0.962)\). An alternate method for displaying the relationship between \(\Delta P\), \(\dot{V}_I\), and \(A_{VP}\) is a two-dimensional plot of \(\Delta P\) vs. \(\dot{V}_I\), as shown in Fig. 5 for each of the six patients. The solid lines provide iso-\(\dot{V}_I\) data that are superimposed on a family of \(A_{VP}\) isopleths (dotted lines) derived from the above equation. This figure illustrates that during flow limitation, \(\Delta P\) increases progressively and \(A_{VP}\) decreases dramatically in all cases.

The Z of the velopharynx was found to vary inversely with \(A_{VP}\). Figure 6 provides all values of Z for all six patients, plotted as a function of simultaneously observed values of \(A_{VP}\). The data are fitted by the relationship \(Z = 0.457/V\). Figure 6A plots Z on a linear scale,
Fig. 4. A: three-dimensional plot of \( A_{VP}/A_{max} \), \( \Delta P \), and \( V_I \) during 49 inspirations (15 non-flow-limited and 34 flow-limited respirations) from 6 patients. Each solid line represents data from single inspiration at a constant \( P_m \). B: common surface fitted to data as Eq. 5 (see RESULTS; \( R^2 \) value = 0.962).

DISCUSSION

The present study provides the first systematic observations of luminal \( A_{VP} \) under dynamic conditions. The results reveal that the interdependence of \( V_I \), \( \Delta P \), and \( A_{VP} \) for all patients is well described by Eq. 5, a relatively simple equation, \((R^2 = 0.962)\) regardless of flow regimes, i.e., flow-limited and non-flow-limited inspirations. This relation signifies that \( V_I \) depends on
Inspirations, the velopharynx progressively nar-
rowed and \( \Delta P \) increased. Accordingly, \( V_i \) was deter-
minal by the balance between \( A_{VP} \) and \( \Delta P \). Specifically, con-
tinuous reduction of \( A_{VP} \) counterbalanced simulta-
nous increase in \( \Delta P \), resulting in constant or decreas-
ing \( V_i \) (negative effort dependence) during IFL. The \( Z \) of the velopharynx depended critically on \( A_{VP} \), and a
single relationship \( Z = 0.457/A_{VP} \) described the inverse dependence of \( Z \) on \( A_{VP} \) for values of \( P_m \) in all
patients. Increments in \( Z \) associated with progressive decreas-
es in \( A_{VP} \) were at least one of the factors causing an increase in \( \Delta P \) during IFL.

We studied patients while nasal CPAP was applied
during sleep, which profoundly diminishes activation of the genioglossus (25). Furthermore, we have previously
shown that this hypotonia is maintained for a single
breath after an abrupt reduction of nasal CPAP (13),
indicating that a single-breath test such as used here
constitutes a useful method for investigating the me-
chanical properties of the hypotonic pharynx under
dynamic conditions.

At the beginning of inspiration, contraction of inspira-
tory pump muscles reduces Pop, which causes airflow
through the collapsible velopharynx. As \( V_i \) increases,
\( P_i \) decreases as a consequence of the increase in kinetic
energy of the air (Bernoulli effect) and as a result of
upstream dissipative energy loss, particularly in the
nasal airway. The decrease in \( P_i \) reduces \( A_{VP} \) in accordance with its dynamic compliance, and this nar-
rowing of the velopharynx further increases kinetic
energy of gas flowing through the segment. The out-
come of these causally interrelated events depends on
the intrinsic mechanical properties of the pharynx, i.e.,
tube law of the pharynx, the initial area determined by
the upstream pressure and the downstream pressure.
If the pharyngeal wall is relatively stiff, \( A_{VP} \) will
decrease little during inspiration, and \( V_i \) will increase
continuously as downstream pressure falls, owing to
contraction of thoracic inspiratory muscles. This is the
case for the hypotonic pharynx when \( P_i \) exceeds \( P_c \) by
\( \geq 5 \text{ cmH}_2\text{O} \). However, the cross-sectional area of a more
compliant velopharynx will decrease during inspira-
tion, such as when \( P_i \) is \( 1–5 \text{ cmH}_2\text{O} \) above \( P_c \), thereby
increasing \( Z \) and lessening the increase in \( V_i \).

Because the caudal margin of the soft palate constit-
tutes a structural discontinuity and because the naso-
pharynx is more compliant than the oropharynx, the
nasopharynx assumes a funnel shape during inspira-
tion, being most narrow at its caudal margin. The
cross-sectional area increases abruptly at the junction
of the velopharynx with the oropharynx. Airflow in
such an expansion tends to display jet flow and flow
separation (16). This can lead to dissipative energy loss
in the oropharynx and a reduction in Pop. Such behav-
ior might account for the observation that \( V_i \) varies
linearly with \( \Delta P^{0.33} \) rather than with \( \Delta P^{0.5} \), as would be
expected from the Bernoulli theorem. Accordingly, a
greater \( \Delta P \) is necessary to produce a given change in
flow when this aerodynamics operates. In addition,
these flow dynamic changes also account for the steep
slope of the relationship between \( A_{VP} \) and \( Z \) at the lower
range of \( A_{VP} \).

A three-dimensional plot of \( A_{VP} \), \( \Delta P \), and \( V_i \) pro-
duces a surface that describes the relationships over a wide
variety of flow regimes. With the use of a collapsible
tube placed in a rigid chamber, \( \Delta P-V_i \) relationships
were demonstrated to depend on experimental condi-
tions, which were given by a combination of upstream
pressure, downstream pressure, and chamber pressure
(3, 5–7, 12, 20). Rodbard (20) and Holt (6, 7) found that
when upstream pressure was maintained constant
above chamber pressure, \( V_i \) at first increased but then
reached a constant value as downstream pressure
decreased. Holt noted that, during flow limitation, the
tube changed its geometry from fully open to partially
collapsed; these observations are compatible with ours.
We observed that at low values of \( P_m \), when collapsibil-
ity is high, \( V_i \) decreased as \( \Delta P \) increased during IFL.
This phenomenon is often referred to as "negative effort

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**Fig. 6.** A: dependence of impedance \( Z \) on \( A_{VP} \) in 6 obstructive sleep
apnea patients (each represented by different symbol). All data from
all patients are plotted, including both flow-limited and non-flow-
limited inspirations. \( Z \) of velopharynx was defined as \( Z = \Delta P^{0.33}/V_i \). B: Logarithmic transformation of ordinate shows that \( Z \) depends on \( A_{VP} \)
even at large values of \( A_{VP} \). Curve passing through data points is
calculated from \( Z = K/A_{VP} \), where \( K = 0.457 \) (see Table 3).

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857PHARYNGEAL DYNAMICS DURING INSPIRATION

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dependence” (14). Jones et al. (10) examined effects of alteration of the collapsibility of the trachea on $\Delta P$-$V_i$ curves. They found that increase in collapsibility led to decreasing maximum flow through the trachea with increasing $\Delta P$ (negative effort dependence) while $V_i$ progressively increased without flow limitation in rigid trachea.

The “waterfall” analogy, proposed by Permutt et al. (17) and Permutt and Riley (18) and applied to upper airway by Schwartz et al. (22) and Smith et al. (24), successfully accounts for $\Delta P$-$V_i$ relationships in a Starling resistor model. The analogy elegantly explains the linear relationship between upstream pressure and the value of flow at the onset of IFL in sleeping normal subjects (22) and in patients with OSA (24). The results of the present study (Fig. 1) confirm these observations in patients with OSA under conditions of reduced activity of the pharyngeal musculature. We observed that $V_i$ increased with increasing upstream pressure in association with a corresponding increase in cross-sectional area of the flow-limiting segment. The waterfall analogy makes no predictions regarding the area of the flow-limiting segment. Rather, the analogy summarizes events by postulating a discontinuity in convective flow, i.e., a waterfall, so that the height of the waterfall does not influence flow rate of the waterfall. However, changes in cross-sectional area at the flow-limiting segment are likely to be significant determinants of $V_i$ during flow limitation. Jones et al. (11) thoroughly examined a role of geometry of a collapsible tube in determining $V_i$ in excised canine trachea. They found that cross-sectional area at the flow-limiting segment was a significant determinant during flow limitation and that cross-sectional area decreased with increasing $\Delta P$ whereas $V_i$ remained unchanged. Our results are in agreement with findings of Jones et al. and suggest that the flow observed when flow is limited by the velopharynx is determined by a balance between increase in $\Delta P$ and decrease in $A_{VP}$.

Our results reveal that snoring and IFL are not necessarily linked mechanical phenomena. We frequently observed the latter but never the former. One possible reason for our failure to observe snoring is that the pharynx was hypotonic during these experiments. The lack of genioglossus activity means that the soft palate and the tongue form a continuous wall of the pharynx. Perhaps snoring cannot occur under these circumstances because of the high mass of the wall. By contrast, when the genioglossus is highly active, the base of the tongue is moved ventrally and a discontinuity occurs between the soft palate and the tongue. This would substantially decrease the mass of the velopharynx and allow the high-frequency oscillation of the soft palate characteristic of snoring.

In summary, a simple mathematical function (Eq. 2) described mutual interrelationships of $A_{VP}$, $\Delta P$, and $V_i$ during inspiration over a variety of flow regimes in the passive pharynx of sleeping OSA patients with a collapsible segment only at the velopharynx. During flow-limited inspirations, the velopharynx progressively narrowed and $P_{ke}$ increased. Simultaneously, the $Z$ of the velopharynx increased, consequent to a progressive reduction in $A_{VP}$, which offsets the simultaneous increase in $\Delta P$, leading to constant or decreasing $V_i$.

REFERENCES


