# Increased Nasal Resistance Induced by the Pressure-Flow Technique and Its Effect on Pressure and Airflow During Speech

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**Although the validity of the pressure-flow technique has been verified in a number of laboratories, some questions still remain. The purpose of this study was to determine whether the procedures involved in estimating orifice size affect the pressure and airflow variables being measured. Twenty subjects with demonstrated velopharyngeal inadequacy on pressure-flow testing (VPO ≥ 0.10 $cm^2$) were assessed under two contrasting conditions. Subjects were asked to produce /p/ in the word "hamper" with a) one nostril occluded by a cork as in pressure-flow testing and b) both nostrils patent. The results indicate that the increased nasal resistance resulting from occlusion of one nostril does not appreciably affect pressure and airflow associated with plosive consonant production in patients with velopharyngeal inadequacy.**

KEY WORDS: *nasal resistance, regulation/control, cleft palate, speech aerodynamics, pressure-flow*

In 1964, Warren and DuBois introduced the pressure-flow technique for estimating velopharyngeal orifice size. Although the validity of the technique has been verified in a number of laboratories (Lubker, 1969; Smith and Weinberg, 1980, 1982), some questions still remain. For example, Yates et al. (1990) and Scherer (1988) believe that the value of the discharge coefficient should be greater than 0.65 because of the theoretical shape of the orifice. Müller and Brown (1980) also cite the unknown geometry of the orifice as a reason for caution when using the pressure-flow equation. In addition, Warren has stated that factors such as irregular motion within the walls of the orifice during speech, as well as downstream turbulence, must be considered when selecting an optimal discharge coefficient (Warren, 1990).

The present study questions another aspect of the pressure-flow technique that has not been previously investigated, namely, does the procedure itself affect the pressure and airflow variables being measured? Although the aerodynamic approach was developed to characterize the relationship between pressure and flow variables, it is of some importance to determine whether the change in airway resistance imposed by the procedure itself affects the absolute values obtained. This is so because recent reports suggest that changes in upper airway resistance produce reciprocal changes elsewhere in the speech system (Warren et al., 1989a, 1989b).

Using bite-blocks (Warren et al., 1980, 1981, 1984), palatal prostheses (Minsley et al., 1987), and simulation of velopharyngeal inadequacy to decrease upper airway resistance (Warren et al., 1989b), Warren and his colleagues have noted that normal adult speakers minimize the effects of various experimental perturbations on intraoral pressures by changing airflow rate, air volume, and duration of the airflow pulse. Postural changes have been noted as well (Warren et al., 1980; Putnam et al., 1986). These responses were similar to what Warren (1986) had described in subjects with velopharyngeal inadequacy.

In the studies cited above, the experimental condition always involved a decrease in upper airway resistance. Responses to increased resistance have not been assessed to date. This is of potential interest since pressure-flow testing involves occluding one nostril, which should increase upper airway resistance. Although the equation for estimating orifice size is not notably affected by an increase in nasal resistance (Smith et al., 1984, 1985; Guyette and Carpenter, 1988), individual parameters such as intraoral pressure and nasal airflow may be altered. The present study addresses this specific issue by attempting to determine whether the procedures involved in estimating orifice size affect the pressure and airflow variables being measured.

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## METHODS

The pressure-flow technique (Warren and Dubois, 1964; Warren, 1984) was used to measure pressure, airflow, and timing variables in a series of patients seen at the University of North Carolina Craniofacial Center. Briefly, the pressure drop across the velopharyngeal orifice (oral pressure minus nasal pressure) was measured by placing one catheter within the mouth and another in the nostril. The nasal catheter was secured by a cork that blocked the nostril, creating a stagnant column of air. Both catheters measured static air pressures and transmitted these pressures to pressure transducers. Nasal airflow was measured by a heated pneumotachograph connected by plastic tubing to the subject's other nostril. In accordance with accepted protocol, the flow tube was always placed in the more patent nostril. The area of the constriction was then calculated from the equation

$$A = \dot{V}/k\ (2\ \Delta P/d)^{1/2}$$

where A = area of orifice, $\dot{V}$ = nasal airflow, k = 0.65, ΔP = oral-nasal pressure, and d = density of air.

Figure 1 illustrates catheter placement and instrumentation for estimating velopharyngeal orifice size and measuring intraoral pressure, nasal airflow, and temporal patterns. The subjects were asked to produce a series of the bilabial plosive consonant /p/ within the carrier word "hamper." The nasal-plosive blend /mp/ was used to stress the palatal mechanism. This phonetic combination also more nearly approximates the degree of closure that occurs during continuous speech (Warren, 1979). Mean peak nasal airflow rate, mean intraoral peak pressure, and mean area of the velopharyngeal orifice during the production of /hamper/ were calculated from a series of three utterances for each subject.

Timing parameters that were measured are shown in Figure 2. The temporal adjustments studied represented timing changes associated with aerodynamic events that occurred during repeated productions of the /mp/ blend in "hamper." The technique used was described by Warren et al. (1985). Duration of pressure and airflow pulses was measured using PERCI-PC Software (Microtronics, Inc., Carrboro, NC).

Twenty children and adults with cleft palate were the subjects for this investigation. They ranged in age from 5.8 to 69.1 years with a mean age of 24.8 years. Several previous investigations have determined that intraoral pressure during speech may vary as a function of age (Subtelny et al., 1966; Bernthal and Beukelman, 1978; Dalston et al., 1988). However, each subject served as his own control in the current investigation. Based upon the group data, the difference between each subject's performance with and without the cork in place was calculated and these data were used in the statistical analyses (paired comparison test). To ensure that potentially important differences in the two procedures would not be overlooked, a significance level of 0.05 was adopted for use in this study.

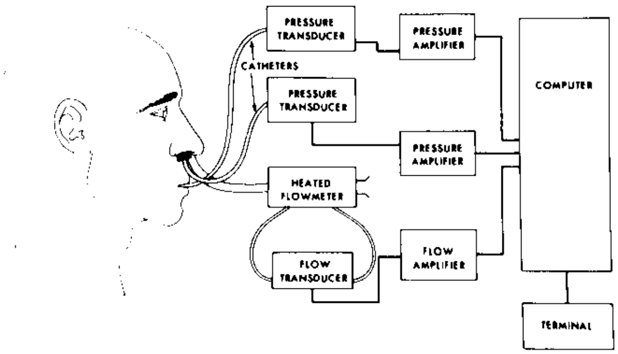


**FIGURE 1 Diagrammatic representation of equipment used to record pressure and airflow (with cork).**

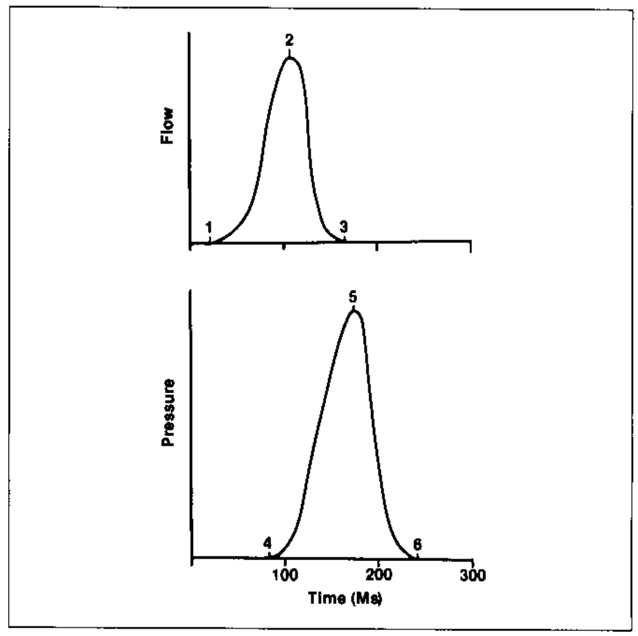


**FIGURE 2 Timing variables for word /hamper/. They included (*1*) begin airflow, (*2*) peak airflow, (*3*) end airflow, (*4*) begin pressure, (*5*) peak pressure, and (*6*) end pressure.**

The only criteria employed during subject selection were that the patients had to have the intellectual capacity and neuromuscular integrity needed to perform the tasks required of them and the patients had to demonstrate an inadequacy of 0.10 $cm^2$ or more on pressure-flow testing. Categorization of a subject as having inadequate velopharyngeal closure is, in part, perceptually based and, in part, aerodynamically based (Warren and DuBois, 1964; Warren, 1979, 1982; Laine et al., 1988; Morr et al., 1989). The reason for limiting the study to those with velopharyngeal inadequacy was to maximize the possible effects of the cork on upper airway pressures and airflow. That is, if closure were adequate, the velum would create enough resistance to mask any possible effects of resistance produced by the cork.

After selecting a subject with velopharyngeal inadequacy for the study, the subject was immediately rerun under a modified condition. The cork and flow tube were removed and a mask was placed over the nose to collect airflow. The oral catheter was placed in the mouth as described earlier (Fig. 3). Intraoral pressure and nasal airflow were measured during the production of the word /hamper/ as described earlier.

The same procedure was also used to measure nasal airway resistance during rest breathing. This approach assumes that resistance across the airway can be estimated by simultaneously measuring the nasal pressure drop and nasal airflow or $R = \Delta P/\dot{V}$ (Watson et al., 1968).

## RESULTS

Table 1 presents the age, velopharyngeal orifice area during speech, and nasal resistance during breathing. Data are not available on nasal resistance for three of the subjects.

Table 2 presents the group means and standard deviations for each of the variables included for study. It can be seen that the value of most variables was smaller when the cork was in place. The only exceptions to this were the duration of the descending portion of the airflow curve, and the corresponding air volume. The increased total airflow curve duration obviously was a secondary effect.

Paired comparison tests were conducted using data presented in Table 2, and Table 3 lists the difference scores and the results of those analyses. The only variable that was significantly affected by the presence of the cork was the duration of the descending portion of the airflow curve. That is, with the cork in place, diminution of airflow in the transition from /m/ to /p/ occurred over a longer period of time.

## DISCUSSION

The results of the present study contrast dramatically with previous studies involving perturbations of the upper airway. In a series of studies involving subjects with congenital velopharyngeal impairment, Warren and his colleagues demonstrated that the respiratory system actively responds to a decrease in upper airway resistance. That is, nasal airflow and volume increased in the presence of velopharyngeal inadequacy (Warren, 1967) or a decrease in orifice resistance (Warren et al., 1989a). An increased respiratory response to a loss of resistance has been reported not only in the cleft palate population but also in individuals with acquired defects of the palate (Minsley et al., 1987, 1988). Experimental perturbations involving bite-blocks (Warren et al., 1980, 1981, 1984), bleed valves (Putnam et al., 1986) or simulation of decreased upper airway resistance (Warren et al., 1989b) caused similar effects. As resistance decreased, airflow rate and volume increased. In some instances pressure fell as resistance decreased, and in other instances pressure re-

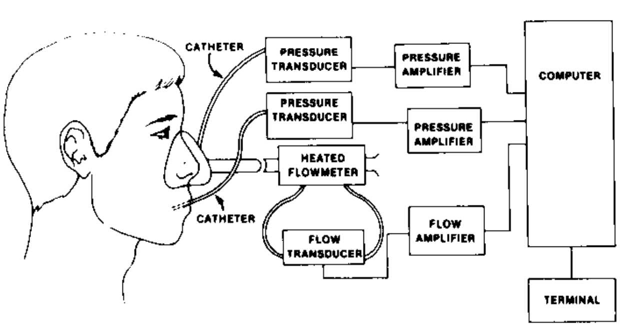


**FIGURE 3 Diagrammatic representation of equipment used to record pressure and airflow (without cork). Intraoral pressure and nasal airflow were measured.**

**TABLE 1 Age, Velopharyngeal Orifice Area, and Nasal Resistance of Subjects Included in This Study**

| *Subject* | *Age (years)* | *VP Area ($cm^2$)* | *Nasal Resistance (cm $H_2O$/L* |
|---|---|---|---|
| KJ | 5.8 | 0.40 | * |
| JS | 9.5 | 0.12 | 4.48 |
| RM | 10.2 | 0.55 | 17.73 |
| JA | 10.8 | 0.16 | 27.50 |
| TW | 12.0 | 0.15 | 10.71 |
| KF | 13.2 | >0.80 | 15.63 |
| TH | 15.0 | 0.11 | 4.26 |
| DC | 15.2 | 0.14 | 4.17 |
| VE | 15.4 | 0.14 | 3.60 |
| CA | 17.3 | 0.14 | 4.27 |
| BM | 17.6 | 0.11 | 8.02 |
| LS | 17.8 | 0.12 | 5.52 |
| BS | 18.0 | 0.15 | 8.08 |
| GP | 32.7 | 0.14 | * |
| KW | 33.7 | 0.46 | 4.97 |
| WD | 41.1 | 0.17 | 149.13 |
| BS | 41.8 | >0.80 | 8.08 |
| MS | 44.3 | 0.57 | * |
| VB | 55.3 | 0.16 | 8.21 |
| WG | 69.1 | 0.10 | 13.25 |

*Patient did not complete the procedure.

**TABLE 2 Means of Variables Included in This Study Across Tests**

| *Variables* | *"Hamper" (with cork) ($\bar{X} \pm SD$)* | *"Hamper" (without cork) ($\bar{X} \pm SD$)* |
|---|---|---|
| Oral pressure (cm $H_2O$) | 4.9 ± 1.8 | 5.3 ± 1.8 |
| Airflow rate (cc/sec) | 239.5 ± 143 | 258.8 ± 113 |
| Pressure duration (msec) | 192.7 ± 28 | 194.3 ± 27 |
| Airflow duration (msec) | 220.3 ± 29 | 208.0 ± 37 |
| Ascending duration (msec)* | 95.3 ± 19 | 97.5 ± 31 |
| Descending duration (msec)* | 127.0 ± 31 | 110.5 ± 27 |
| Ascending volume (cc)† | 11.9 ± 6 | 14.1 ± 8 |
| Descending volume (cc)† | 15.6 ± 11 | 14.5 ± 7 |
| Airflow volume (cc) | 27.0 ± 15 | 28.7 ± 13 |

*Ascending and descending durations are the duration of the ascending and descending airflow curves.
†Ascending and descending volumes are the airflow volumes.

**TABLE 3 Means of Difference Scores Across Tests**

| *Variables* | *Difference Scores* | *P value* |
|---|---|---|
| Oral pressure (cm $H_2O$) | 0.43 | 0.07 |
| Airflow rate (cc/sec) | 19.32 | 0.58 |
| Pressure duration (msec) | 1.67 | 0.69 |
| Airflow duration (msec) | 12.33 | 0.09 |
| Ascending duration (msec) | 2.17 | 0.68 |
| Descending duration (msec) | 16.50 | 0.001 |
| Ascending volume (cc) | 2.19 | 0.28 |
| Descending volume (cc) | 0.96 | 0.68 |
| Airflow volume | 1.72 | 0.63 |

mained about the same. For example, Putnam et al. (1986) noted that pressure fell considerably in their labial valve studies but varied very little across a wide range of bite-block conditions. They attributed this difference to the fact that the tongue was able to compensate for the bite-block opening but not for the bleed-valve opening. In support of this, they found that respiratory effort increased more under bleed-valve conditions. Similar findings were obtained in studies involving simulation of velopharyngeal inadequacy and subsequent loss of upper airway resistance (Morr et al., 1988; Warren et al., 1989a). Intraoral pressure fell and respiratory effort increased. It should be noted, however, that in all of the above studies intraoral pressures were constantly maintained above 3.0 cm $H_20$ for consonants despite the decrease in airway resistance.

One recurring observation in previous studies was that the responses to decreased orifice resistance seemed to reflect an attempt to maintain an adequate level of intraoral pressure during consonant productions. In general, pressures were maintained at levels above 3.0 cm $H_20$ despite some perturbations that resulted in rather significant drops in airway resistance. Conversely, results of the present study suggest that only small adjustments were made in response to the added resistance imposed by the nostril cork. There are several possible explanations for this finding. Perhaps the most plausible reason is that all the subjects were able to produce intraoral pressures above 3.0 cm $H_20$ despite having velopharyngeal impairment. The attempt to maintain an adequate level of pressure was already successful, and there was no need to compensate for the added resistance provided by addition of a cork in one nostril.

Another possibility is that the open nostril compensated for the blocked nostril. Hairfield et al. (1987) reported that when one nostril is occluded during breathing, the other nostril accommodates for the increase in resistance by increasing patency by about 10 percent. Furthermore, this accommodation can be more dramatic in individuals with clefts that affect the nasal valve. Warren et al. (1990) recently reported that the nasal valve of individuals with clefts can be blown open during expiration up to 130 percent of its normal size. If such changes occurred during speech, they could moderate the effect of a cork blocking one nostril. We are currently investigating whether this accommodation actually occurs during speech.

Among the various parameters included for study in this investigation, only one was found to be significantly affected by the presence or absence of a cork in one nostril. As shown in Table 3, the duration of the descending portion of the airflow curve was significantly shortened when the cork was not in place. The reason for this is not entirely clear. It may be that the uncorked nostril simply allowed for more rapid dissipation of nasal airflow as the patient attempted to close down the velopharyngeal port in the transition from /m/ to /p/. Whatever the explanation may be for this single exception, it appears reasonable to conclude that the standard technique used for pressure-flow testing of patients with velopharyngeal inadequacy does not appreciably affect the variables being measured.

Finally, it should be pointed out that the presence of a cork might be expected to have less of an effect upon the measurements studied here when velopharyngeal resistance is high. However, the results of preliminary statistical analysis (t-test) showed that the differences of all variables observed across cork conditions for the six patients with velopharyngeal areas greater than 0.20 $cm^2$ were not significantly different from those for the 14 subjects with velopharyngeal areas less than 0.20 $cm^2$.

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# Commentary

The question posed in the preceding article by Drs. Liu, Warren, and Dalston is a straight forward and logical one. I am curious to know why it took more than 25 years to ask it, not just by these investigators but by others who have employed a similar procedure.

The pressure-flow technique was first introduced by Warren and DuBois in 1964. Their landmark article set the stage for an impressive number of subsequent investigations in which this technique has been used to estimate velopharyngeal orifice size and measure intraoral pressure, nasal airflow, and temporal patterns (Warren, 1982; Warren et al., 1985). The use of the technique has given scientists ample opportunity to examine the behavioral response of a system when a loss occurs in vocal tract resistance, particularly in individuals with velopharyngeal inadequacy (VPI). Despite the multitude of measurements made and resultant interpretations, a fundamental question remained unanswered — until now. "Do the procedures used in the pressure-flow technique affect pressure and airflow variables?"

The answer provided by Liu et al. is as easily answered as it is queried. Essentially, the effect of an induced resistance upon a system using corks and tubing in individuals with VPI is said to be negligible. A considered merit of this finding is that a correction factor is not necessary when using the pressure-flow technique to obtain measurements such as estimates of velopharyngeal orifice size, airflow, pressure, and nasal resistance.

Research by Warren (1967) and Dalston et al. (1988) have revealed alterations in respiratory effort and articulatory production in the presence of a *decrease* in resistance in the upper airway in individuals with VPI. It was also noted that these same individuals could maintain an intraoral pressure of 3.0 cm $H_2O$ during non-nasal productions. In the present study in which an *increase* in resistance was induced, minimal response adjustments were documented. The proposed explanations for this effect by Liu et al. are reasonable. I suspect that some individuals with VPI may alter respiratory effort, albeit minimally, with an increase in resistance. Inductive plethysmography, a technique used in previous investigations (Morr et al., 1987) may provide some information about respiratory effort in response to an increase in resistance in the upper airway.

Additionally, the maintenance of intraoral pressure above 3.0 cm $H_2O$ may occur as a consequence of the increase in resistance created by lingual contacts at various points in the vocal tract, a concept that has received prior attention by Warren (1986). For example, individuals exhibiting pharyngeal fricatives tend to interrupt the airstream between the tongue and pharyngeal wall, whereas those with glottal stop substitutions interrupt the airstream at the level of the glottis.

Regardless of the place of interruption, the result is an increase in resistance in the upper airway. With the aid of nasopharyngoscopy I have observed that when abnormal tongue postures are present during speech production, they are repeatedly achieved within a speaker. As a result, the place of resistance and its magnitude might remain fairly constant, aiding in the maintenance of intraoral pressure. I would also guess that even as these individuals modified the place of articulation, the point of resistance would change with little observable alteration in intraoral pressure. Although not directly addressed in this investigation, I am confident that these issues will be either confirmed or refuted in forthcoming articles by Warren and his colleagues.

Liu et al. are to be thanked for asking and answering such a basic question regarding the effects of the procedures used in the pressure-flow technique.

Well done.

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