A Comparison of Response Characteristics of Airflow and Pressure Transducers Commonly Used in Rhinomanometry

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A Comparison of Response Characteristics of Airflow and Pressure Transducers Commonly Used in Rhinomanometry

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Abstract—Although the ranges in which pneumotachographs evidence linear output to static flows are documented in the literature, measures of output reliability or the stability of calibration functions resulting from the input of dynamic nonsinusoidal flows (such as those which occur during nasal breathing) have not been investigated. Furthermore, it is not known whether the type of requisite pressure transducer used in conjunction with the pneumotachograph influences the pneumotachograph’s linearity, output reliability, or dynamic response. To provide information on these points, we determined the dynamic and static responsiveness of three pneumotachographs commonly used in rhinomanometry, in combination with three requisite pressure transducers. In general, a) output reliability depended on the pneumotachograph/pressure transducer combination and was not readily predictable from the reliabilities of the individual components, b) heating increased pneumotachograph reliability, and c) differences in accuracy existed among transducer combinations at high, but not low, flow frequencies. In addition, results from the calibration syringe study (in which the pneumotachograph is calibrated with dynamic nonsinusoidal flows) suggested that: a) a single calibration factor, as supplied by most pneumotachograph manufacturers, is inadequate for accurately measuring the full range of flows produced in sniffing and breathing tasks; b) the measurement of complex waveforms, even when the dominate frequencies of such waveforms are low, requires pneumotachographs that accurately respond to relatively high frequencies; and c) the use of dynamic nonsinusoidal flows (as opposed to static flows) to calibrate pneumotachographs results in a calibration function with higher reliability.

INTRODUCTION

MODERN DEVICES for monitoring airflow and pressure have greatly advanced our understanding of the dynamics of nasal respiratory function. The early water manometer, from which the force of the subject’s breath was used to infer nasal airflow, was superseded in the 1950’s by electronic transducers which accurately monitor flows and which provide almost instantaneous response, recording, and display of nasal breathing cycles [1]. Today many different types of electronic airflow transducers are commercially available, including turbine, hot wire, ultrasonic, laminar flow elements, and ceramic-, Fleisch-, and screen-type pneumotachographs [2]. Of these transducers, the Fleisch- and screen-type pneumotachographs best fit the criteria for measurement of nasal airflow. In such devices, flow rate is determined by the measurement of the pressure differential across an airflow resistor [3].

While the ranges in which pneumotachographs evidence linear output to static flows are available in the literature [4]-[6], information on several other important parameters is lacking. For example, the influence of the type of requisite pressure transducer on output reliability has not been examined and the stability of output functions resulting from the input of dynamic nonsinusoidal flows has not been carefully assessed. In addition, a comparison of the methods used to input flows through the pneumotachograph for calibration and the methods used to calculate calibration factors has not been performed.

The purpose of the present series of four experiments was to provide information on these points. Specifically, we determined the output reliability, linearity, and dynamic responsiveness of three pneumotachographs commonly used in rhinomanometry, in conjunction with three requisite pressure transducers. In addition, the reliabilities of the pneumotachograph calibration calculation procedures resulting from the input of static or dynamic airflow were compared.

GENERAL METHODS

Transducers Tested

We selected two Fleisch-type pneumotachographs (Fleisch no. 2 and Fleisch no. 3) and a screen-type pneumotachograph (Hans Rudolph Model 3700) for testing (See Table I). All three models contained heating elements, which reduce both condensation and the temperature variation during the breathing cycles [2], [7].

We tested three widely-used pressure transducers (Valadyne Model MP45-2, Sentra Model 261-1, and Celesco Model LCVR-2) responsive to the differential pressure range of the pneumotachographs (See Table II). These pressure transducers measure the low differential pressure (i.e., < 2 mm H2O) produced across the resistive element of the pneumotachographs.

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TABLE I

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Dead Air Space (cc)</th>
<th>Differential Pressure at 1 L/s (mm HOH)</th>
<th>Maximum Flow Rating (L/min)</th>
<th>Resistive Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hans Rudolph</td>
<td>5</td>
<td>2.23</td>
<td>100</td>
<td>Mesh Screen</td>
</tr>
<tr>
<td>Fleisch no. 2</td>
<td>40</td>
<td>2.56</td>
<td>180</td>
<td>Parallel Capillary Tubes</td>
</tr>
<tr>
<td>Fleisch no. 3</td>
<td>92</td>
<td>16</td>
<td>360</td>
<td>Parallel Capillary Tubes</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Pressure Range (cm H2O)</th>
<th>Voltage Output (Volts)</th>
<th>Full Scale (mL/min)</th>
<th>Demodulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sentra</td>
<td>+6.25</td>
<td>0 to 5</td>
<td>±1%</td>
<td>Not Required</td>
</tr>
<tr>
<td>Celsuco</td>
<td>+2.50</td>
<td>±10</td>
<td>±0.1%</td>
<td>Celsuco LCCD</td>
</tr>
<tr>
<td>Valadyne</td>
<td>+2.00</td>
<td>±10</td>
<td>±0.5%</td>
<td>Valadyne CDI9-871</td>
</tr>
</tbody>
</table>

Dependent Measures

Output reliability, linearity, and dynamic response of the pneumotachograph–pressure transducer combinations were assessed using tests of a) fixed flow (experiment 1), b) frequency response (experiment 2), and c) syringe calibration (experiment 4). In order to assess the output reliability of the pressure transducers independent of the pneumotachographs, a pressure transducer reliability test was conducted (experiment 3). In addition, we compared the various methods used to derive calibration functions (experiment 4).

In general, output reliability was established by calculating the percent deviation of the recorded input signal from the value calculated to predict the pressure of flow (i.e., calibration factor) at each point along the flow or pressure continuum. Thus, the higher the percent deviation value, the lower the output reliability value. The magnitude of the Pearson correlation coefficient established between the input flow rates and the resulting digitized flow signal was used to quantify linearity. Dynamic responsiveness was determined by examining the amplitude ratios resulting from the input of sinusoidally changing flows. These dependent measures are discussed below in further detail.

EXPERIMENT 1: FIXED FLOW TEST

One of the more common methods of calibrating flow measuring devices is the procedure of passing known static flows through a device and recording the resulting output signals. Studies which have used this method have not measured output reliability and do not agree on the degree of linearity at high and low flow rates [6], [8]. Using the fixed flow procedure, we a) compared the output reliability of the nine pneumotachograph–pressure transducer combinations, b) determined whether heating the pneumotachograph element influenced reliability, and c) evaluated transducer linearity within two flow ranges (i.e., 2 to 12 L/min in 2 L/min increments and 10 to 50 L/min in 10 L/min increments).

PROCEDURE

Airflows produced by a 1.5 hp 12 gal tank compressor were calibrated with precision rotometers (Fisher & Porter Model 10A6130), and directed through the pneumotachograph under test [9], [10]. The voltage output of the requisite pressure transducer was converted into integers using a 12-b analog-to-digital converter at a rate of 10 Hz for a duration of 5 s, and processed by a Franklin 1200 microcomputer. The eleven flow rates were presented in an ascending/descending order; this flow presentation staircase was repeated 8 times. The pneumotachographs were tested with this procedure twice, once heated to 37°C and once at room temperature (21°C). The percent deviation from the mean calibration value was calculated for each data point.

RESULTS

Separate regression functions were fit to each of the two ranges of flow data for the pneumotachograph–pressure transducer combinations to establish if the linearity differed between these ranges. A test of difference between independent correlations with Bonferroni correction for inflated alpha [11], [12] was used to compare the r values resulting from the regressions. This analysis indicated that no significant differences existed between the two flow ranges for any of the transducer combinations (ps > 0.40).

To establish whether pneumotachograph type, pressure transducer type, pneumotachograph temperature, or flow...
range influenced overall system reliability, we subjected output reliability values to a four-way analysis of variance. Essentially, this analysis compared within device variability to between device variability. This analysis revealed significant pneumotachograph type \( F(2, 184) = 3.752, p < 0.01 \), pressure transducer type \( F(2, 184) = 42.148, p < 0.001 \), and pneumotachograph temperature \( F(1, 184) = 49.807, p = 0.001 \) effects. Output reliability did not differ between the two flow ranges \( F(1, 184) = 2.311, p > 0.90 \).

Analysis of the pneumotachograph main effect using post hoc polynomial contrasts with Bonferroni correction for inflated alpha [13] revealed a significantly lower output reliability for the Fleisch no. 2 \( \text{Mean} = 15.25, \text{SD} = 15.99 \) than for the Hans Rudolph \( \text{Mean} = 10.90, \text{SD} = 11.78 \) and Fleisch no. 3 \( \text{Mean} = 11.70, \text{SD} = 11.56 \) pneumotachographs \( F(1, 184) = 9.559, p < 0.05 \). The values of the latter two transducers did not differ significantly from one another \( F(1, 184) = 1.913, p > 0.15 \). Analysis of the pressure transducer type effect revealed a significantly higher output reliability for the Celesco \( \text{Mean} = 3.828, \text{SD} = 3.528 \) than for the Valadyne \( \text{Mean} = 15.50, \text{SD} = 15.68 \) pressure transducers \( F(1, 184) = 14.96, p < 0.001 \), which did not differ significantly from the other \( F(1, 184) = 0.11, p > 0.90 \).

The pneumotachograph temperature effect resulted from a higher output reliability of the transducer systems when the pneumotachographs were heated \( \text{Mean} = 7.75, \text{SD} = 9.02 \) than when they were not heated \( \text{Mean} = 17.49, \text{SD} = 15.11 \). Changes in the calibration factor for the Fleisch no. 3, Fleisch no. 2, and Hans Rudolph pneumotachographs following heating were +7.5%, +10%, and -12%, respectively.

As can be seen in Fig. 1, although the Fleisch no. 3 pneumotachograph evidenced the lowest output reliability when used in conjunction with the Celesco and Valadyne pressure transducers (as compared to the other pneumotachograph), it evidenced the best output reliability when used with the Sentra pressure transducer relative to the other two pneumotachographs. This inconsistency of the rank of the output reliability for the Fleisch no.3 as compared to the other pneumotachograph was statistically reflected by a pneumotachograph by pressure transducer interaction \( F(2, 184) = 12.64, p < 0.001 \).

A smaller influence of pneumotachograph temperature on output reliability of transducer systems which used the Fleisch no. 3 pneumotachograph resulted in a temperature by pneumotachograph interaction \( F(2, 184) = 4.07, p < 0.02 \) (Fig. 2). The higher output reliability of the Celesco pressure transducer under both temperature states resulted in a pressure transducer by temperature interaction \( F(2, 184) = 14.96, p < 0.001 \) (Fig. 3).

**EXPERIMENT 2: FREQUENCY RESPONSE**

Since respiratory parameters are dynamic, it is important that flow measuring devices have rapid response capabilities to accommodate the measurement of such changes. A convenient method for determining the ability of a transducer to measure dynamic events is to examine its response to a sinusoidally changing input over a wide frequency range. In order to express the response of the transducer, the amplitude ratio over the frequency spectrum was examined. Ideally, the closer the amplitude ratio to unity, the better the frequency response.

**Methods**

The method used to assess frequency response was similar to that described by Jackson and Vinegar [14]. This
method required the construction of a frequency response chamber. A vertical partition was inserted inside a 30 cm³ square Plexiglas box in order to create two chambers, one twice as large as the other. A 50 W bass speaker (Realistic Model 40-13318) was mounted on this partition with the speaker membrane facing the smaller chamber. The larger chamber was sealed except for a pressure port on which a fast responding pressure transducer was connected (Sentra Model 239). The smaller chamber was similarly sealed, except for one 2 mm i.d. pressure transducer port and one 22 mm i.d. flow transducer port (located directly opposite the speaker). The flow transducer to be tested was mounted on the latter port. Measurement of the pressure changes within the box allowed for the determination of distortion of the flow signal resulting from the frequency response of the testing apparatus. Any such distortions were accounted for mathematically. The speaker was oscillated at frequencies ranging from 10 Hz to 120 Hz. Although some of these frequencies are higher than the primary dominate breathing frequency, breathing waveforms contain nondominate frequencies as high as 30 Hz and such frequencies are standard for assessing pressure and flow transducer characteristics [4], [5], [14]. For each frequency, the data points from 10 cycle periods were collected and ensemble averaged for each pneumotachograph-pressure transducer combination. A microcomputer with a 12-b analog-to-digital converter, sampling at a rate ten times that of the speaker frequency, processed the transducer's signals.

Results

In order to determine if pneumotachograph type, pressure transducer type, or frequency influenced the frequency response of the airflow measurement system, we used a two-way analysis of covariance to analyze the amplitude ratio data. This analysis revealed that pneumotachograph type \( F(2, 98) = 6.72, p < 0.001 \), pressure transducer type \( F(2, 98) = 15.45, p < 0.001 \), and test frequency \( F(1, 98) = 190.37, p < 0.001 \) influenced the amplitude ratio. An interaction between the amplitude ratios of the pressure transducer type and pneumotachograph type was found \( F(4, 98) = 12.96, p < 0.001 \). This interaction was probably the result of the matching of the working pressure ranges of the pneumotachographs to the optimal working pressure ranges of the pressure transducers.

Analysis of the pneumotachograph effect revealed that the Fleisch no. 3 \( \text{Mean} = 4.05, \text{SD} = 3.01 \) had a significantly higher amplitude ratio that the Fleisch no. 2 \( \text{Mean} = 3.25, \text{SD} = 2.57 \) and the Hans Rudolph \( \text{Mean} = 2.78, \text{SD} = 2.78 \) pneumotachographs \( F(1, 98) = 11.67, p < 0.002 \). The amplitude ratios of these latter two transducers did not differ from one another \( F(1, 98) = 1.76, p > 0.15 \) (Fig. 5). Analysis of the pressure transducer effect revealed that the Valadyn pressure transducer \( \text{Mean} = 4.48, \text{SD} = 3.27 \) demonstrated a significantly higher amplitude ratio than that of the Celesto \( \text{Mean} = 2.72, \text{SD} = 2.44 \) or the Sentra \( \text{Mean} = 2.87, \text{SD} = 2.37 \) pressure transducers \( F(1, 98) = 30.71, p < 0.001 \). The latter two pressure transducers did not differ significantly from one another \( F(1, 98) = 0.182, p > 0.50 \) (Fig. 6).

EXPERIMENT 3: PRESSURE TRANSDUCER RELIABILITY

Pressure transducer reliability was evaluated independent of the pneumotachographs. This provided a vali-
dation for the pressure transducer findings of experiment 1, b) a logical basis for the selection of the pressure transducer to be used in the next experiment, and c) insurance that the output reliability measure derived for these devices included pressures throughout the transducers’ full pressure spectrum.

Method

The output signals of the three pressure transducers were evaluated at eight different pressures. The pressures at eight different percentages of each transducer’s full scale rating (i.e., ±25%, ±50%, ±75%, and ±100%) were determined, and used as the testing pressures. For each pressure, 50 data points were sampled over a 5 s period. A Franklin 1200 microcomputer with a 12-b analog-to-digital converter was used to sample the pressure transducer’s voltage values at each testing pressure.

Results

Comparisons of the pressure transducer output reliabilities by a one-way ANOVA revealed that pressure transducer type influenced output reliability [F(2, 21) = 5.78, p = 0.01]. Further analysis indicated that the Celesco pressure transducer evidenced higher reliability than either the Valadynne or Sentra pressure transducer [F(1, 21) = 7.24, p = 0.05]. The output reliability of the latter two transducers did not differ from one another [F(1, 21) = 4.33, p < 0.10].

Experiment 4: Calibration Syringe Test

Although it is common to present pneumotachograph linearity data by displaying a pressure versus flow curve [4], [5], [10], data presented by Yeh et al. [15] suggest that a conductance curve (flow/pressure versus pressure) may be a more sensitive measure of linearity. In addition, calibration of flow transducers using a calibration syringe is easier and more accurate than traditional methods [9], [15], [16]. Thus, in this experiment, we used a 3-L calibration syringe to induce a specific volume of air through the pneumotachographs under evaluation. Since the use of the calibration syringe to induce air flow through the pneumotachographs produces a wide range of changing flows, which have frequencies not unlike those of human breathing, such a procedure may better simulate nasal breathing than other calibration methods (i.e., fixed flow).

Methods

The pneumotachograph was attached to the end of a 3-L Hans Rudolph calibration syringe via a Plexiglas adapter. The syringe was pumped in one of three ways: a) high flow rate (75 L/min) to low flow rate (10 L/min); b) constantly increasing (from 10 L/min to 45 L/min) and constantly decreasing flow rates (from 45 L/min to 10 L/min); and c) low flow rate (10 L/min) to high flow rate (75 L/min). These flow patterns were chosen to simulate those of the nasal respiratory tract [17]. Each of these flow patterns was induced through each pneumotachograph ten times in both airflow directions.

The output signal of the Celesco pressure transducer, in conjunction with one of the three aforementioned pneumotachographs, was processed by a Franklin 1200 microcomputer via a 12-b analog-to-digital converter at a sample rate of 100 Hz for a duration of 5 s. The pressure values recorded were integrated to find the volume of the flow waveform in terms of digital pressure units. A calibration factor was then calculated from the proportion of the digitized flow curve volume to the true syringe volume. This calibration factor was then weight-averaged into a master array of conductance values for each flow value.

Following the complete testing of a pneumotachograph device, an array of resistance values was derived from the master array of conductance values. First- and second-order polynomial regression equations (Table III), which related the integer pressure values to the calibration values (represented as conductance or resistance), were then fit to the data. To determine which equation had the best fit, the r values of these equations were compared.

A percent deviation measure was calculated for the calibration factors for all three pneumotachographs in combination which the Celesco pressure transducer derived by a) the best regression equation, b) the best regression equation using data collect using the fixed flow method, and c) a single calibration factor (as incorporated in experiment 1) using data from the present experiment. In this way, when we included the percent deviation data from the first experiment, the influence of the two flow input methods and the two calibration calculation methods on output reliability could be determined.

Results

The r values for the first- and second-order polynomial regression equations are presented in Table IV. The higher the r value, the stronger and more reliable the pressure-calibration-value relationship. The highest r value calculated for all pneumotachographs was found when the data were fit to a second order regression equation using resistance as the dependent variable (equation (3) in Table III).

A test for difference between independent correlations with Bonferroni correction for inflated alpha [11], [12] was used to compare the r values from the fits of the regression equation. The Hans Randolph pneumotachograph showed the highest r value (Fig. 7), which was significantly higher than the r values from either of the two Fleisch pneumotachographs [ps < 0.001]. The r value for the Fleisch no. 2 was significantly higher than that of the Fleisch no. 3 [p < 0.001].

A two-way ANOVA was used to compare the influence of both the flow input and calibration calculation methods on the output reliabilities. This analysis revealed significant influences of both the flow input method [F(1, 3921) = 394.45, p < 0.001] and calibration calculation method [F(1, 3921) = 276.93, p < 0.001] on output reliability. As seen in Table V, the syringe calibration method for flow input and the regression calculation method resulted
in higher output reliabilities, and the combination of these two methods resulted in the highest output reliability.

**General Conclusions and Discussion**

The present series of studies evaluated the output reliability, linearity, and frequency response of several widely-used and currently-marketed flow and pressure transducers. The results of this research indicate that these transducers vary considerably regarding such characteristics, and that complex interactions exist among specific pressure and flow measuring devices. These studies further suggest that the use of a resistance curve, rather than a single calibration factor, provides a more reliable measure of flow. In addition, the use of dynamic nonsinusoidal flows, analogous to those encountered during breathing, rather than static flows results in a higher output reliability estimate.

This research supports the notion that pneumotachograph heating produces a more reliable and accurate airflow measurement, presumably by reducing condensation within the resistive element of the pneumotachograph and thereby creating a more laminar flow. However, changes in pneumotachograph temperature alter the calibration as a result of changes in air viscosity, air density, and air volume. In the case of the screen-type pneumotachograph, its reliance on air density for flow measurement caused its calibration factor to decrease by 0.75% / °C following heating. Likewise, reliance of the Fleisch-type pneumotachographs on air viscosity caused their calibration factors to increase by 0.47% / °C for the Fleisch no. 3 and 0.63% / °C for the Fleisch no. 2 following heating. Although Hobbes calculated an increase of approximately 1.00% / °C for the Fleisch no. 2, our results and those of others suggest an increase of roughly 0.50% / °C. Regardless of the specific magnitude of this effect, it appears important that the pneumotachograph system is calibrated at the temperature at which it will be used for airflow measurement.

The change in air characteristics during heating of the pneumotachograph not only alters the calibration factor, but also alters the working differential pressure range of the pneumotachograph. If a pressure transducer is more sensitive to pressure changes within a certain range, changes in the working pressure range of the pneumotachograph will alter the output reliability of the air measurement system. Such an effect could explain the pressure transducer by pneumotachograph interaction. Indeed, heating of the pneumotachograph influenced the output reliability of both the Valdyne and Sentra pressure transducers.

The data of our study show that the manufacturers’ performance specifications cannot be relied upon to establish the comparative performance of pressure and flow transducers. For example, on the basis of such specification the Valdyne pressure transducer should outperform the

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**Table III**

Regression Equations Used to Describe Conductance-Value/Pressure and Resistance-Value/Pressure Data. (IPV = Integer Pressure Values, \(C1, C2, R1, \) and \(R2\) are the Equation Coefficients Derived from Regression Analysis)

<table>
<thead>
<tr>
<th>Method</th>
<th>Flow Input Method</th>
<th>Average for Calculation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Calibration Factor</td>
<td>4.756 (0.747)</td>
<td>2.964 (0.084)</td>
</tr>
<tr>
<td>Regression</td>
<td>3.310 (0.530)</td>
<td>1.113 (0.085)</td>
</tr>
<tr>
<td>Average for Flow Input Method</td>
<td>4.033 (0.115)</td>
<td>2.062 (0.054)</td>
</tr>
</tbody>
</table>

**Table IV**

Values of the Regression Equations used for Flow Transducer Calibration to Relate Resistance or Conductance to Digitized Pressure Values. The Celsco Pressure Transducer was Used in Conjunction with all Pneumotachographs. Values were Determined from the Data Collected during the Calibration Syringe Test

<table>
<thead>
<tr>
<th>Syringe Type</th>
<th>Hans Rudolph</th>
<th>Fleisch no. 2</th>
<th>Fleisch no. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Order Resistance</td>
<td>0.926</td>
<td>0.805</td>
<td>0.573</td>
</tr>
<tr>
<td>Second Order Conductance</td>
<td>0.924</td>
<td>0.793</td>
<td>0.559</td>
</tr>
<tr>
<td>First Order Resistance</td>
<td>0.650</td>
<td>0.763</td>
<td>0.474</td>
</tr>
<tr>
<td>First Order Conductance</td>
<td>0.649</td>
<td>0.753</td>
<td>0.467</td>
</tr>
</tbody>
</table>

---

Fig. 7. Resistance values for Hans Rudolph Model 3700 pneumotachograph when used in conjunction with the Celsco pressure transducer. The calibration syringe was used to input the flow into this pneumotachograph (as described in experiment 4) in order to obtain these values. Linear and polynomial regression lines derived from these data using resistance as the dependent variables (see (2) and (4)) are superimposed on the data.
Sentra pressure transducer, and the pneumotachograph–
pressure transducer systems which used the Valadyne
pressure transducer should perform better than systems
which used the Sentra pressure transducer. Our data do
not support either one of these predictions. Similarly, the
pneumotachograph/pressure transducer interaction in ex-
periment 1 demonstrated that the Fleisch no. 3 pneumo-
tachograph worked better when in combination with the
Sentra pressure transducer, even though its calculated er-
ror would be the largest of all the pneumotachograph/
pressure transducer combinations examined.\footnote{The
error of the airflow measurement system as a result of the
pressure transducers can be calculated by the formula: flow
measurement error (l/s) = pressure transducer error (cm
H\textsubscript{2}O) \div pneumotachograph pressure at 1
1/s. Mean error values for the Sentra, Valadyne, and Celeco pressure
transducers in combination with all pneumotachographs were 2.13, 0.34,
and 0.085 L/min, respectively.}

The poorer performance of the Fleisch no. 3 pneumo-
tachograph in the calibration syringe test than in the fixed
flow test can be attributed to a) the presence of higher and
more turbulent flows in the calibration syringe test than
the fixed flow test, b) the poor frequency response of this
transducer, or c) a combination of these characteristics.
High flow rates probably do not account for the Fleisch
no. 3’s performance since its large diameter opening
should be associated with greater linearity and reliability
at such flow rates [8]. Since irregular waveforms, such as
those produced by the calibration syringe or nasal breath-
ing, are composed of many frequencies [19], a transducer
must be able to measure the highest frequency of the
waveform accurately. Our observation that the amplitude
ratio of the Fleisch no. 3 was small at low frequencies
suggests that the frequency response criterion of 5 Hz put
forth by Sullivan et al. [2] for a ventilation monitoring
device is not a sufficient criterion for selecting devices for
the measurement of nasal breathing. In light of this ob-
servation, a higher frequency criterion, such as that sug-
gested for diagnostic spirometry flow rate measurement
(i.e., 12 Hz) [19], [20], might be more appropriate.

Experiment 4 found that the relationship between resis-
tance and the differential pressure of the pneumotacho-
graph is not linear across the range of flows measured
and that a stronger relationship occurs when resistance values
rather than conductance values are used in the regression
equations. This is likely the result of a higher calculation
error for the conductance values than for the resistance
values, which results from the smaller magnitude of the
conductance values (i.e., for the Hans pneumotachograph
conductance values ranged from 0.038 to 0.043 across the
flow continuum; corresponding resistance values ranged
from 16.092 to 23.175). Indeed, the numerical precision
of the algorithm used to process such values can have a
significant influence on the error of the results [16].

Both transducer design engineers and clinical–technical
personnel involved in rhinomanometric measurement
should be aware of the information presented in this pa-
er. We have evaluated present day rhinomanometric
measurement transducers and have discussed their perform-
ance in relation to published specifications. Engineers
who develop rhinomanometric systems for airflow mea-
surement can use our results to assist in developing spec-
fications, designing transducer systems, and selecting ap-
propriate transducer types when assembling a system to
measure physiological pressures and flows from the res-
piratory system. Clinical–technical personnel who use
rhinomanometric equipment should use dynamic nonsinu-
osoidal flows to calibrate their pneumotachograph (ex-
periment 4). The resulting digitized data should be fit to
a second-order polynomial equation with resistance as the
dependent variable. The adoption of these techniques will
decrease the measurement error, and lead to greater ac-
curacy and reliability. For an explanation of a method for
deriving resistance (or conductance) values when using
dynamic nonsinusoidal flows, the reader should refer to
Yeh et al. [15].

It should be noted that factors such as age, frequency
of cleaning, and prolonged use without proper main-
tenance likely effect the reliability, dynamic response, and
accuracy of pressure and flow transducers. Obviously,
proper maintenance, calibration, and the replacement of
inadequately performing transducers should be made on a
regular basis. Unfortunately, the evaluation of the precise
effects of these factors are beyond the scope of this paper.

In general, the Hans Rudolph model 3700 pneumo-
tachograph was the most accurate pneumotachograph tested.
This device showed a) the highest output reliability in the
fixed flow tests, b) the smallest amplitude ratio in the fre-
cuency response test, and c) the strongest resistance–
value–pressure relationship. Although the Fleisch no. 3
pneumotachograph evidenced high output reliability in the
fixed flow test, its larger dead air space (Table I) probably
elicited its unsatisfactory frequency response perfor-
ance (cf. Fry et al. [5]). Overall, the Celesco model
LCVR-2 pressure transducer showed the best character-
istics for measuring differential pressure of the pneumo-
tachographs tested.

In summary, the present research demonstrates five
points. First, differences exist in reliability, linearity, and
frequency response characteristics among pneumotacho-
graph and pressure transducer types. Second, such differ-
ences can influence the performance of pneumotacho-
graphs in combination with requisite pressure transducers
in complex ways not readily predictable \textit{a priori} from their
individual performances. Third, criteria for determining
the frequency specifications needed for an airflow mea-
surement system cannot be based on the dominate airflow
frequency of non-sinusoidal airflow (i.e., breathing fre-
cquency). Fourth, resistance curves are more accurate and
reliable than a single calibration factor. Fifth, the use of
nonsinusoidal flows to calibrate airflow measurement de-
vices appears to produce more accurate calibration factors
than the use of static flows.

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REFERENCES


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