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Laboratory Note

Errors in Pneumotachography as a Result of Transducer Design and Function

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Differential pressure transducers used to sense the pressure differentials across the resistive elements of Fleisch pneumotachographs may, in the presence of transient pressure changes in the airway due to intermittent positive-pressure ventilation, cause errors in the flow signals. Such error results from differences between the volume of the two compartments of some differential pressure transducers and causes differences in the time constants of volume change of the two compartments. The magnitude of the error is a function of the difference between time constants and the rate of pressure change within the airway. For example, using a Fleisch number 1 pneumotachograph–Statham PM 15 differential pressure transducer system (internal compartment volumes 6.67 and 35.50 cm^3), application of a transient pressure of 30 cm H_2O for 0.4 second caused apparent flows of 100–120 ml/sec. The magnitude of the apparent flow signal was reduced but not abolished by adjusting the external volume of the tubing. Using a Sanborn 270 differential pressure transducer (internal compartment volumes 4.70 and 3.42 cm^3) under similar conditions, the apparent flow signal was small. (Key words: Pneumotachography errors; Transducer design.)

PNEUMOTACHOGRAPHY is a convenient method of measuring respiratory gas flow and volume during monitoring and investigation of gas exchange and respiratory mechanics in patients receiving intermittent positive-pressure ventilation (IPPV).[1] Pneumotachography has also been used to measure air flow and volume during testing of ventilator function using mechanical analogs of the respiratory system. As a result of transient pressure changes within the airway during these maneuvers, there may be an error in the sensing of the pressure differential across the resistive element of the pneumotachograph by the differential pressure transducer. This error is the result of differences between volumes in the two compartments of some differential pressure transducers. The potential magnitude of the consequent error in flow and volume measured by pneumotachography during IPPV may be large and, for example, during the monitoring of neonates with respiratory distress syndrome, it may be 25–50 per cent of the flow signal.

Methods

The effects of transient pressure changes on the sensing of the pressure differentials across Fleisch number 1 and number 0 pneumotachographs by differential pressure transducers were examined using Sanborn 270 and Statham PM 15 differential pressure transducers. The two pressure ports of the Fleisch pneumotachographs were attached to the Sanborn 270 ports by 20 cm of plastic tubing (ID 3 mm) and to the Statham PM 15 by 30 cm (ID 3 mm) and 10 cm (ID 6 mm) of plastic tubing. Shortening the tubing connecting the pneumotachograph to the Statham PM 15 transducer increased the error in the flow signal. The Sanborn 270 transducer was activated by, and the ensuing signal processed by, a Sanborn 311 transducer–amplifier–indicator unit. All data were recorded on a Grass model 7 polygraph. The Fleisch pneumotachograph and transducer systems were calibrated over a

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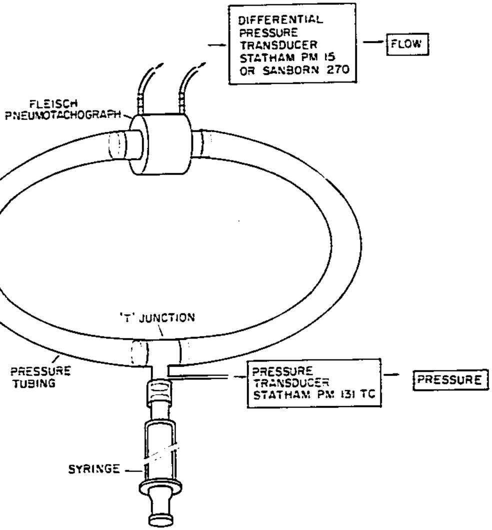

FIG. 1. Diagram of the circuit and apparatus used to simulate transient pressure changes within the airway and the Fleisch pneumotachograph during intermittent positive-pressure ventilation and to measure the apparent flow signals induced by these pressure changes when using Statham PM 15 or Sanborn 270 differential pressure transducers.

range of flows using a calibrated-orifice flowmeter; they were linear over the flow range encountered in this study. The flow ranges were 10–100 ml/sec and 20–200 ml/sec, respectively, for the number 0 and the number 1 Fleisch pneumotachographs. The orifice flowmeter was shown to be accurate and linear over this flow range by timed collections of gas flow into a Collins 6-liter spirometer.

Transient pressure changes within the pneumotachograph which simulated the pressure changes during IPPV were achieved as follows. Each end of the Fleisch pneumotachograph was attached to a 20-cm length of pressure tubing with an internal caliber similar to that of the pneumotachograph, and the other ends of the pressure tubing were connected to the transverse ends of a T connection (fig. 1). The third end of the T connection was connected by pressure tubing to a glass syringe, which was lubricated with glycerin and did not leak over the pressure range encountered. Positive and negative pressure changes of as much as 30 cm H_2O were achieved by moving the plunger of the syringe, and the rise times were 0.3 to 5.0 seconds. Pressure within this system was sensed by a Statham PM 131 TC ± 2.5–350 pressure transducer.

"TUNING" THE DIFFERENTIAL PRESSURE TRANSDUCER

The differences between time constants in the two chambers of the differential pressure transducers were also evidenced by the demonstration of pressure signals during simultaneous transient application of the same pressure to both sides of the transducers (via a Y connection). This also provides a convenient method for "tuning" the transducer by adjusting the external tubing volume until the signal of the pressure differential is abolished or reduced to a minimal value.

Results

As a result of the application of transient positive or negative pressures of 30 cm H_2O to the Fleisch number 1 pneumotachograph–Statham PM 15 differential pressure trans-

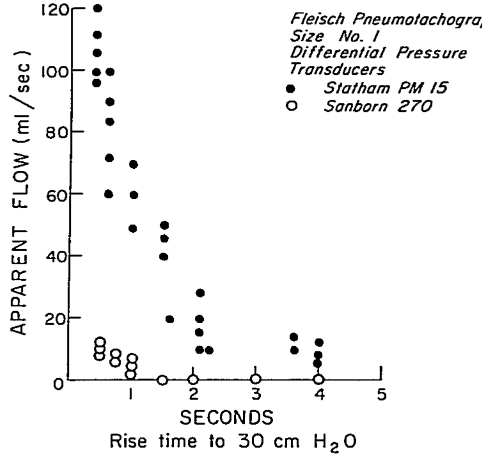

FIG. 2. Relationship between the apparent flow signals sensed from a Fleisch number 1 pneumotachograph by Statham PM 15 and Sanborn 270 differential pressure transducers as a result of a pressure of 30 cm H_2O applied over 0.4 to 4.0 seconds. See text for description of apparatus.

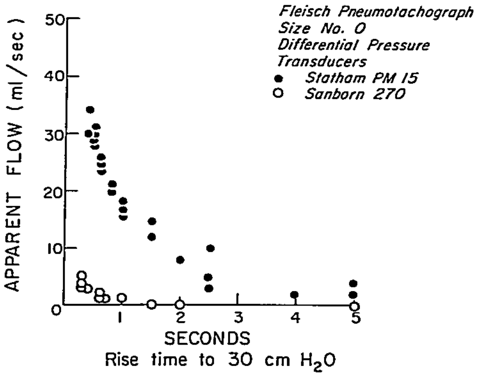

FIG. 3. Relationship between the apparent flow signals sensed from a Fleisch number 0 pneumotachograph by Statham PM 15 and Sanborn 270 differential pressure transducers as a result of a pressure of 30 cm H_2O applied over 0.5 to 5.0 seconds. See text for description of apparatus.

ducer system over rise times of 0.4 to 4.0 seconds, the apparent flow signals were 120 to 12 ml/sec. Flow signals were inversely proportional to rise times of the pressure. By contrast, using the Fleisch number 1 pneumotachograph–Sanborn 270 differential pressure transducer system, the apparent flow signals in response to 30 cm H_2O pressure applied over rise times of 0.5 to 4.0 seconds were 8–12 ml/sec at a rise time of 0.5 second and zero at a rise time of 1.5 seconds (fig. 2). Using the Fleisch number 0 pneumotachograph–Statham PM 15 system, the apparent flow signals in response to the same pressure applied over rise times of 0.4 to 5.0 seconds were 34 to 6 ml/sec. However, using the Fleisch number 0 pneumotachograph–Sanborn 270 system, apparent flow signals in response

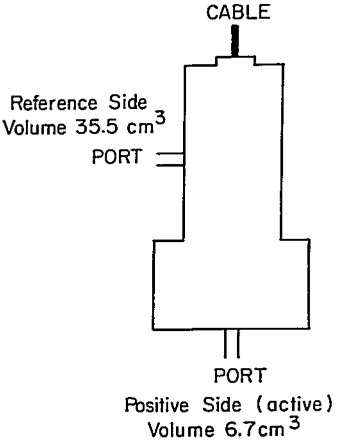

FIG. 4. Diagram of Statham PM 15 differential pressure transducer.

to the same pressure transients applied over rise times of 0.3 to 5.0 seconds were 5 ml/sec at a rise time of 0.3 seconds and zero at a rise time of 1.5 seconds (fig. 3).

"Tuning" the Sanborn 270 by reducing the length of the tubing connected to the P 1 port to 12 cm reduced the apparent flow signal sensed from the Fleisch number 0 pneumotachograph in response to a transient pressure of 30 cm H_2O applied over a rise time of 0.3 second to less than 2 ml/sec. Similar attempts were made to "tune" the Statham PM 15 transducer by increasing the volume of the tubing attached to the port of the active side (fig. 4, table 1). Although the apparent flow signal was reduced to 25 to 50 per cent of the previous values, it could not be reduced to negligible levels.

Discussion

The physical principles of the pneumotachograph are described by the Hagen-Poiseuille law for laminar, nondivergent flow in rigid smooth tubes.

$$\dot{Q} = (P_1 - P_2)\,\frac{\pi \cdot r^4}{8 \cdot l \cdot \eta}$$

where $\dot{Q}$ is the flow, $P_1 - P_2$ is the pressure differential across the resistive element, r and l are the radius and the length of the resistive element, respectively, and η is the viscosity of the gas. Previous studies have disclosed the errors in pneumotachography that result from turbulent flow and from flows outside the linear flow range of the pneumotachograph.[2, 3] Recently, Finucane *et al.*[4] demonstrated that changes in the flow profile induced by changes in the upstream geometry altered the relationship between flow and the pressure drop across the resistive element of the pneumotachograph. During IPPV the gas volumes measured by pneumotachography are compressed by the applied pressure; Grenvik and Hedstrand[1] correct this volume to BTPS by using the mean tracheal pressure. However, none

TABLE 1. Pressure Ranges, Differential Pressure Limits, and Volumes of the Internal Compartments of Differential Pressure Transducers Used to Sense the Pressure Differential across Fleisch Pneumotachographs

Manufacturer and Model	Excitation and Type of Transducer	Pressure Range (mm H_2O)	Differential Pressure Limits (mm H_2O)	Internal Volume of Compartments	
				cm^3	cm^3
Sanborn 270	5V, 2400-Hz, linear variable differential transformer (LVDT)	±400	±2,000	Port 1 4.70	Port 2 3.42
Statham PM 15	5 V, DC or AC, strain gauge	±26	±2,480	Active side 6.67	Reference side 35.50
PM 97	10 V, DC or AC, strain gauge	±36	±71	17.61	36.17
PM 283	5 V, DC or AC, strain gauge	±107	±213	1.83	2.17

Validyne Engineering Company manufactures a very-low-range differential pressure transducer (Model DP45) which is suitable for pneumotachography and is symmetrically constructed.

of these factors accounts for the error in the flow signal during compression of the gas observed in the present study. Moreover, for an ideal gas, theoretically viscosity is independent of pressure. At high pressures intermolecular forces increase viscosity and at low pressures viscosity is proportional to pressure as a result of an increase in the mean free-molecular path.[5, 6] The pressure changes encountered in the present study have negligible effects on the viscosity of the gas.

Differences between the time constants of the two compartments of the transducers are responsible for the errors in flow signal demonstrated during compression or rarefaction of gas in the pneumotachograph–transducer systems and the pressure differentials demonstrated during simultaneous application of the same pressure to the two chambers of the differential pressure transducers. This is consistent with the volumes of the compartments of these differential pressure transducers (table 1). Although the Statham PM 15 is the most suitable of the Statham series on the basis of sensitivity for sensing the pressure differential across the pneumotachograph, it has the greatest volume difference between the two compartments (6.67:35.50 cm^3) (table 1, fig. 4) and therefore requires the greatest adjustment of the external volume in order to reduce the error in the flow signal. The Statham PM 283 has compartments which are similar in volume, but because of its lower sensitivity it requires greater amplification.

The magnitude of the error in flow and volume measurement when using a Statham PM 15 differential pressure transducer with a Fleisch number 1 pneumotachograph during IPPV or while testing a ventilator with a mechanical analog of the respiratory system is difficult to predict. However, from the data presented, it may be anticipated that during IPPV of a neonate whose inspiratory time is short and who has mechanical abnormalities of the respiratory system and therefore needs high ventilating pressures, the error may be large. For example, Thomas *et al.*[7] and Owen-Thomas *et al.*,[8] ventilated infants who had respiratory distress syndrome, in whom airway pressures were 20–40 cm H_2O and respiratory frequencies 60–70 breaths/min (inspiratory times 0.3 to 0.5 sec, depending on the inspiratory:expiratory time ratio); inspiratory flows were 50–200 ml/sec. Reasoning from their data, the magnitude of the errors in flow signals could be 25 to 50 per cent. Although the errors in flow signals arising from the Statham PM 15 could be reduced by increasing the external volume of one of the catheters connecting the pneumotachograph to the Statham transducers, it was not possible to abolish them.

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