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A Modified Pitot tube for the Accurate Measurement of Tidal Volume in Children

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A device using modification of a Pitot tube has been designed for measurement of tidal volume in infants and small children. Its accuracy was compared both *n vitro* and *n vivo* to that of a calibrated pneumotachograph (Fleish #1) designed for a similar flow range. *In vitro* measurement of air flow with the modified Pitot tube (MPT) was within 5% of the pneumotachograph readings over a range of 1–60 l/min. Similar accuracy was found with measurement of tidal volumes from 20 ml to 1 l, delivered by a calibrated volume-cycled ventilator using a variety of inspiratory flow rates. Tidal volume measurements with the MPT were compared to the pneumotachograph using helium, oxygen, carbon dioxide, and a range of nitrous oxide/oxygen mixtures. A manual control was incorporated into the MPT electronics to allow direct measurements of tidal volume with different nitrous oxide/oxygen concentrations. *In vivo*, the insertion of the MPT into the patient circuit caused no apparent changes in ventilatory parameters in children under 20 kg. Measurement of tidal volumes with the MPT agreed to within 8% of pneumotachograph readings. The low dead space (1.5 cc) and light weight (12 gm) of the MPT confer advantages over the pneumotachograph (15 ml dead space and a weight of 90 gm) for routine use in pediatric anesthesia. (Key words: Anesthesia: pediatrics. Measurement techniques: Pitot tube. Ventilation: tidal volume.)

THERE ARE FEW DEVICES available for accurate measurement of tidal volume in infants and small children. Although the pneumotachograph has been shown to accurately measure gas flows and tidal volumes in small patients, it has three particular disadvantages: 1) it is relatively heavy, 2) it has a large dead space, and 3) it requires recalibration when the gas composition is changed. In contrast, the pediatric Wright respirometer is less affected by gas composition but, like the pneumotachograph, it is heavy, bulky, and adds a large dead space to the patient circuit. Additional dead space may make little difference in a circle system, but, with the Ayre's t-piece, it becomes a serious problem. Furthermore, both devices are heated electrically during prolonged use to prevent the condensation of water vapor which may lead to inaccurate measurements.

The Pitot tube is a device traditionally used to measure fluid velocity, and has been used in aeronautics for many years to determine airspeed. The Pitot tube allows the estimation of velocity from the dynamic or ram pressure (P) of the flowing gas by determining the difference between the total pressure and the static pressure in the gas stream. Bernoulli's law of fluid dynamics states that the velocity (V) is directly proportional to $\sqrt{P/D}$, where D is the gas density. Hence, gas velocity can be derived from a Pitot tube by taking the square root of the difference between total and static pressure.

The Pitot tube can be modified to measure respiratory variables by mounting the pressure sampling tubes inside a cylindrical pipe. It is then possible to measure inspiratory or expiratory gas flow. Tidal volume may also be derived by integrating the gas flow with time.

Large-diameter modified Pitot tubes (MPT) are used routinely to measure peak expiratory flow in adults.[1] The accuracy of a large-diameter modified Pitot tube for measuring smaller gas velocities has been compared to the pneumotachograph.[1] Although the measurements with the Pitot tube were accurate, the pressure signal required piecewise electronic linearization. In addition, the dead space of even the smallest MPT was too large for insertion into an anesthetic circuit. Estimation of much smaller gas flows has been achieved in birds using a miniaturized Pitot tube.[2] This latter design has a very small dead space (less than 0.1 ml), but is more applicable to qualitative rather than quantitative flow measurements.

We have designed a device based on the Pitot tube principle for use with the Ayre's t-piece circuit in order to measure tidal volumes in infants and small children during general anesthesia. In this report, we evaluate the accuracy of the modified Pitot tube in both the laboratory and the operating room.

Materials and Methods

The modified Pitot tube (MPT) consists of a short plastic conduit with two very small pressure sensing tubes lying within the lumen of the conduit in parallel to the gas flow but facing in opposite directions (fig. 1). The pressure sensing tubes are connected to a differential pressure transducer by means of a pair of long narrow plastic tubes. The conduit has standard 15-mm ISO connections and fits into the patient circuit between the fresh gas flow and endotracheal tube (fig. 2). Three sizes have been made according to the size of the internal diameter of the conduit; a 3.5-mm for children under 3 kg, a 5-mm for under 20 kg, and an 8-mm for

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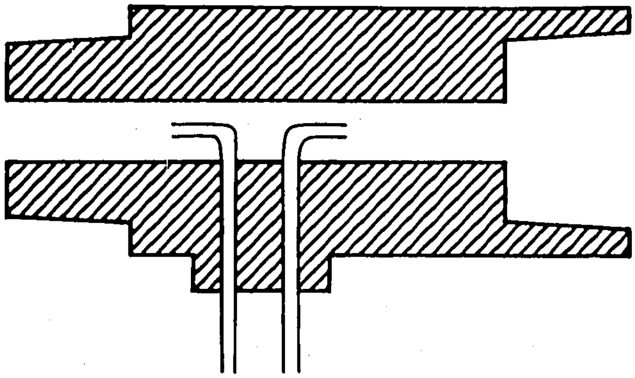

FIG. 1. Schematic diagram of modified Pitot tube with centrally placed pressure sensing tubes facing opposite directions.

children > 20 kg. The dead space of these MPTs are 0.5 ml, 1.5 ml, and 5 ml, respectively. In this study, all data refer to the 5-mm conduit. The dimensions of this MPT are; length 5 cm, external diameter 19 mm, and weight 12 gm.

Tidal volume is estimated by integrating the square root of the differential pressure signal with time. An electronic sample and hold circuit provides a continuous display of the tidal volume.

To validate the accuracy of the MPT, flow and volume measurements obtained with the MPT were compared to those measured with a Fleish pneumotachograph (Hewlett Packard® size #1). The accuracy of the pneumotachograph had previously been confirmed with flows up to 60 l/min of air with a wet spirometer. Two-point calibration of the MPT for air flow was performed by means of rotameter at 0 and 10 l/min. A

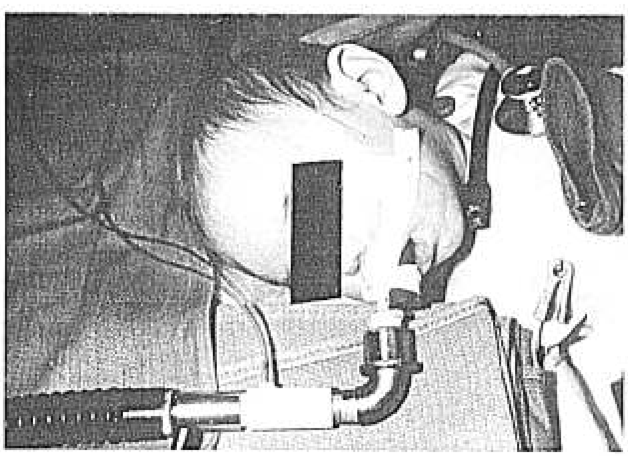

FIG. 2. Photograph of the modified Pitot tube inserted in the patient circuit between the fresh gas line and the angle piece of a pediatric circuit.

comparison of flow measurement was made by delivering dry medical air to the two devices in series using flows from 1 l/min to 60 l/min. Known tidal volumes of five gases; air, oxygen, nitrous oxide, carbon dioxide, and helium, were delivered *via* a calibrated piston ventilator.[3] Tidal volume measurements from 20 cc to 1 l were delivered to both the MPT and pneumotachograph in series at a range of gas flows from 1 l/min to 60 l/min. All measurements were repeated with the serial positions of the MPT and pneumotachograph reversed.

To determine the effect of the nitrous oxide concentration on the tidal volume measurement with the MPT, a range of nitrous oxide/oxygen mixtures from 100% nitrous oxide to 100% oxygen were studied. Nitrous oxide concentrations were determined using a calibrated LB-2 infrared gas analyzer with a nitrous oxide detector. All tidal volumes measured with the MPT were repeated with gas flows in both the directions in order to validate the accuracy of the MPT during both the inspiratory and expiratory phases.

In vivo, studies were performed to establish the accuracy of the MPT under conditions of varying gas flow and humidity. The tidal volume measurements obtained with the MPT were compared to those obtained with the pneumotachograph in both ventilated and spontaneously breathing patients undergoing general surgical and orthopedic procedures. Thirty infants and children were studied, and their weights ranged from 3–18 kg.

In those patients who were mechanically ventilated, anesthesia was maintained with d-tubocurare, 65% N_2O/35% O_2, and halothane using an Air-Shields Ventimeter. The pneumotachograph was inserted into the patient's circuit between the endotracheal tube and fresh gas flow after induction. The MPT was inserted adjacent to the pneumotachograph 10–15 min later once the end-tidal CO_2 had reached equilibrium. Simultaneous recordings of tidal volume were then observed on both MPT and pneumotachograph. The MPT remained in the patient circuit until the end of surgery to determine the effects of water vapor and condensation on the accuracy of the measurements. End-tidal CO_2 and ventilator pressures were recorded throughout the study period. In the group breathing spontaneously, all patients had their tracheas intubated, and they were anesthetized with 65% N_2O/35% O_2 and halothane. The MPT was inserted into the patient circuit after the surgery had commenced. Respiratory rate, heart rate, and end-tidal carbon dioxide were recorded before and after insertion of the MPT.

Statistical analysis was performed using least squares linear regression analysis and the coefficient of variation (r^2).

Results

Fresh gas flows from 1–60 l/min of dry medical air measured with the MPT agreed to within 5% of the pneumotachograph readings (fig. 3). Tidal volumes measured with the MPT correlated with the pneumotachograph up to inspiratory flow rates of 60 l/min ($r^2 = 1$). The discrepancy between inspiratory and expiratory tidal volumes was less than 2%.

The composition of the fresh gas significantly affected measurements of tidal volume with both the MPT and the pneumotachograph (fig. 4). The MPT underestimated the tidal volume for any gases with a density less than air, whereas it overestimated the tidal volume for gases with a density greater than air. The pneumotachograph overestimated the tidal volume for those gases with a viscosity higher than that of air, and underestimated the tidal volume for those gases with a viscosity lower than that of air.

Increasing the nitrous oxide concentration in the fresh gas caused the MPT to progressively overread (fig. 5). The experimental results were compared to the theoretical relationship derived from Bernoulli's equation. The least squares linear regression for the experimentally derived data was a straight line (the solid line) with the MPT overestimating the tidal volume by 16% in pure nitrous oxide ($r^2 = 0.996$). The MPT electronics were modified to include a manual control for compensation of the nitrous oxide concentration in the fresh gas. Direct readings of tidal volumes in the operating theater were then possible without using a calibration curve.

Tidal volumes measured with the MPT in intubated patients correlated to within 8% of pneumotachograph readings. End-tidal P_{CO_2} and peak inspiratory pressure did not change after the MPT was placed in the circuit with the exception of larger children (15–18 kg) in whom a small increase in peak inspiratory pressure (<2 cm) occurred due to the resistance of the 5-mm head. Water vapour did not affect the MPT sensing tubes even after 3 h of anesthesia, and tidal volume measurements remained constant during this time.

Respiratory rate, end-tidal P_{CO_2}, respiratory pattern, and heart rate were unchanged when the MPT was inserted into the anesthetic circuit of spontaneously breathing patients. *In vitro,* resistance of the MPT at fresh gas flows of 10, 20, and 30 l of oxygen was 0.2, 0.4

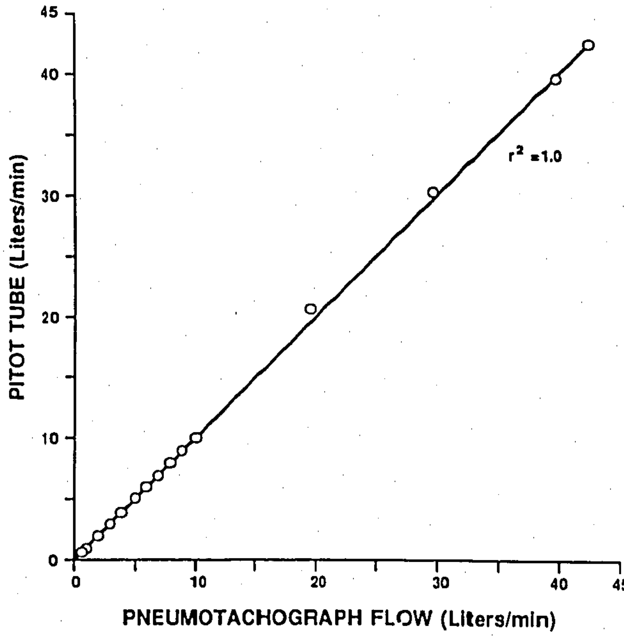

FIG. 3. Air flow measurement with the modified Pitot tube compared to that measured with the pneumotachograph ($r^2 = 1$).

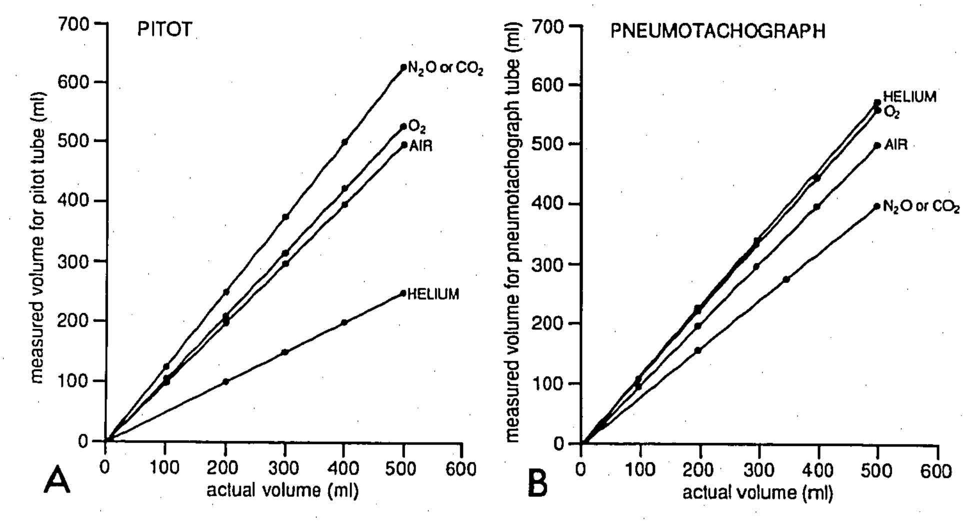

FIG. 4. A comparison of known volumes of helium, oxygen, air, nitrous oxide and carbon dioxide with volumes measured using the modified Pitot tube (*A*) and pneumotachograph (*B*).

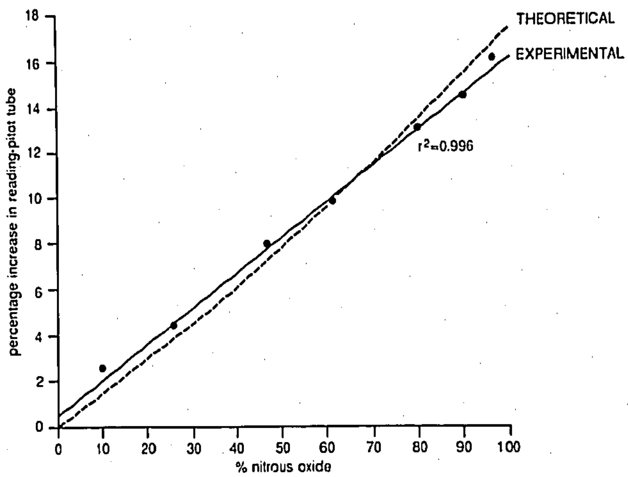

FIG. 5. The effect of different nitrous oxide/oxygen mixtures on volume measurement with the modified Pitot tube. Solid dots represent experimental results. The solid line is the best fit line for the data ($r^2 = 0.996$). The dashed line is derived from the theoretical relationship between percent nitrous oxide in oxygen and the percent error on volume measurement with a Pitot tube calibrated for air.

and 0.6 cm H_2O/l/min, respectively. The resistance of the pneumotachograph was less than 0.1 cm H_2O/l/min for flows in the same range.

After a 10-min warmup, electronic drift was not found to be a major problem with tidal volumes exceeding 200 ml. During ventilation with smaller tidal volumes, however, frequent re-zeroing of both instruments was required for accurate results. Half-hourly re-zeroing was found to be adequate for most cases.

Discussion

The MPT, as described above, accurately measures tidal volume in anesthetized mechanically ventilated children weighing between 3 and 18 kg. It does not significantly affect either the resistance or the dead space of the t-piece circuit. Because the MPT is small and lightweight, it may prove to be a clinically useful tool in pediatric anesthetic practice.

The accuracy of both the pneumotachograph and the MPT depends on gas composition. For example, the MPT overestimates the tidal volume by 10% in a gas mixture of 65% nitrous oxide in oxygen, whereas the pneumotachograph underestimates tidal volume by 17% in a similar gas mixture. In order to correct for this measurement error with the MPT, a compensating dial was incorporated. The MPT may, therefore, be preferred, particularly when changes in gas composition are anticipated.

This compensating dial provides an accurate and direct measurement of tidal volume in the operating room in the presence of any nitrous oxide/oxygen mixture without the need for recalibration. The overestimation of tidal volumes with the MPT in the presence of increasing concentrations of nitrous oxide in oxygen correlates closely with the theoretically derived values based on Bernoulli's equation, and demonstrates the closeness of the response of the MPT to the theoretical model. Discrepancy in tidal volume measurements with the MPT during induction and emergence from anesthesia may be attributed, in part, to differences in gas concentrations between inspired and expired gases. From theoretical considerations, however, we do not expect the duration of these problems to exceed 5 min. Although the flow through the MPT is almost certainly turbulent above a certain limit, we have found no discontinuity in the measurement from low to high flows. This fortuitous finding makes it possible to use a small diameter MPT for a range of flows which would exceed the useful range of a pneumotachograph of similar diameter. The accuracy of the pneumotachograph is also very sensitive to the flow entry conditions. We have found no such problems with the small diameter MPT, which has a similar flow range.

Ventilation is difficult to assess in small infants during anesthesia. Breath-by-breath monitoring of ventilation requires either accurate end-tidal carbon dioxide or tidal volume measurements. Although carbon dioxide measurements are possible, they may be unreliable unless the sampling site is near the tip of the endotracheal tube.[4] Because of the special sampling techniques required for reliable CO_2 monitoring in small infants, tidal volume measurements may be easier. In addition, pressure-limited ventilators may deliver reduced tidal volumes when the lung or chest wall compliance decreases or the endotracheal tube becomes obstructed. Sudden decreases in tidal volume could be detected immediately if an MPT were present in the anesthetic circuit. Moreover, the simplicity of this device makes it easy to manufacture inexpensively, and may allow routine measurement of tidal volume in infants and small children.

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