special communications

Computerized determination of pneumotachometer characteristics using a calibrated syringe

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YEH, MINKEN P., REED M. GARDNER, TED D. ADAMS, AND FRANK G. YANOWITZ. *Computerized determination of pneumotachometer characteristics using a calibrated syringe.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 53(1): 280–285, 1982.—A computerized method has been developed to determine the conductance characteristics of pneumotachometers. Conductance values of the flowmeter, which correspond to all pressure values, can be determined by a weighted averaging technique, when multiple strokes of a precision 3-liter calibrated syringe are used. The conductance values then allow the measured differential pressures to be converted, point by point, into flows. The accuracy of measured volumes is within ±0.5% for a 100-stroke calibration process, and calibration with 50 strokes provides ±1% accuracy. The method improves the accuracy of the on-line measurements of ventilation, O_2 consumption, and CO_2 production during exercise.

conductance; flowmeter

PNEUMOTACHOMETERS that provide nearly linear pressure-flow relationships have been in use for several decades (4, 5, 8). Although these devices are widely accepted for on-line computerized analysis in pulmonary function laboratories, exercise laboratories (2, 11), and intensive care units (10), there are still several problems associated with their use. The frequent calibration of pneumotachometers, which is required to maintain accuracy, is generally a complex and time-consuming task, as it usually requires a source of constant airflow (e.g., vacuum cleaners, unbalanced Tissot spirometers). More convenient calibrated syringes, with volume accuracies of ±1% (traceable to the National Bureau of Standards), have recently been made available for under $300 and have been recommended for spirometer calibration by the American Thoracic Society (1).

Theoretically, if one could push or pull one of these syringes at a constant speed, a known constant flow could be generated. Using several known flows, one could then determine the conductance (flow/pressure) characteristics of the pneumotachometer and linearize the device. Unfortunately, it is very difficult to generate constant and accurate flows with a syringe or with any other device. This report describes a method that uses a computerized weighted-averaging technique and a calibrated syringe to determine the conductance (or linearity) characteristics of pneumotachometers.

METHODS

The data-acquisition system (Fig. 1) is comprised of a 3-liter calibrated syringe (A&M Systems), a pneumotachometer (Fleisch no. 3, Dynasciences), a pressure transducer (Validyne DP45), and a carrier amplifier (Validyne CD12). The computer (Data General NOVA 4) samples the differential pressure signals from the pneumotachometer through a 10-bit analog-to-digital (A/D) converter at a rate of 100 Hz. The amplifier gain is adjusted so that the full range of the A/D converter corresponds to a flow range of 0–600 l/min (10 l/s).

A pressure-time curve is generated with each stroke of the 3-liter syringe. Figure 2 (left) illustrates pressure-time curves from two different strokes of the syringe. Figure 2 (right) is a histogram of the pressure points generated from the pressure-time curves of Fig. 2 (left); it also forms the basis for the weighted-average conductance-determination method.

The following simplified numerical example is presented to illustrate how conductance values are determined. This example describes the use of a 3-liter syringe and a 2-bit A/D converter [generating values of 0, 1, 2, and 3 A/D units (ADU) for differential pressure signals], with a sampling rate of 100 Hz (sampling interval, 0.01 s). Two strokes of the syringe are applied for calibration. Only the three conductance values (corresponding to pressure values of 1, 2, and 3 ADU) are required, since *value 0* has no contribution to the volume. *Stroke 1* consists of 11 points of 1 ADU pressure value, 4 points of 2 ADU pressure value, and 2 points of 3 ADU pressure value, and *stroke 2* consists of 2, 4, and 4 points of 1, 2, and 3 ADU pressure values, respectively.

Volume is obtained by integrating the flow-time curve (or summation of the digital flow signal). Flow can be

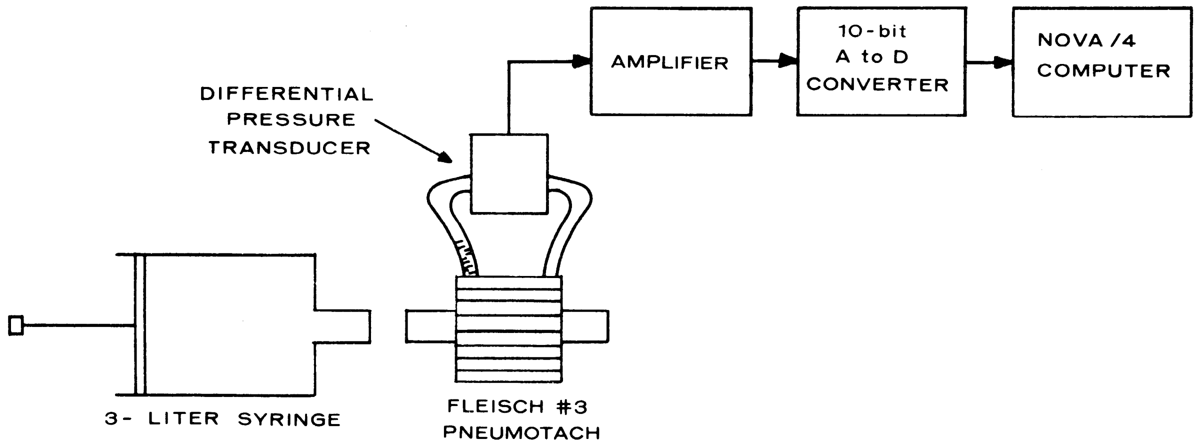

FIG. 1. Block diagram of data-acquisition system.

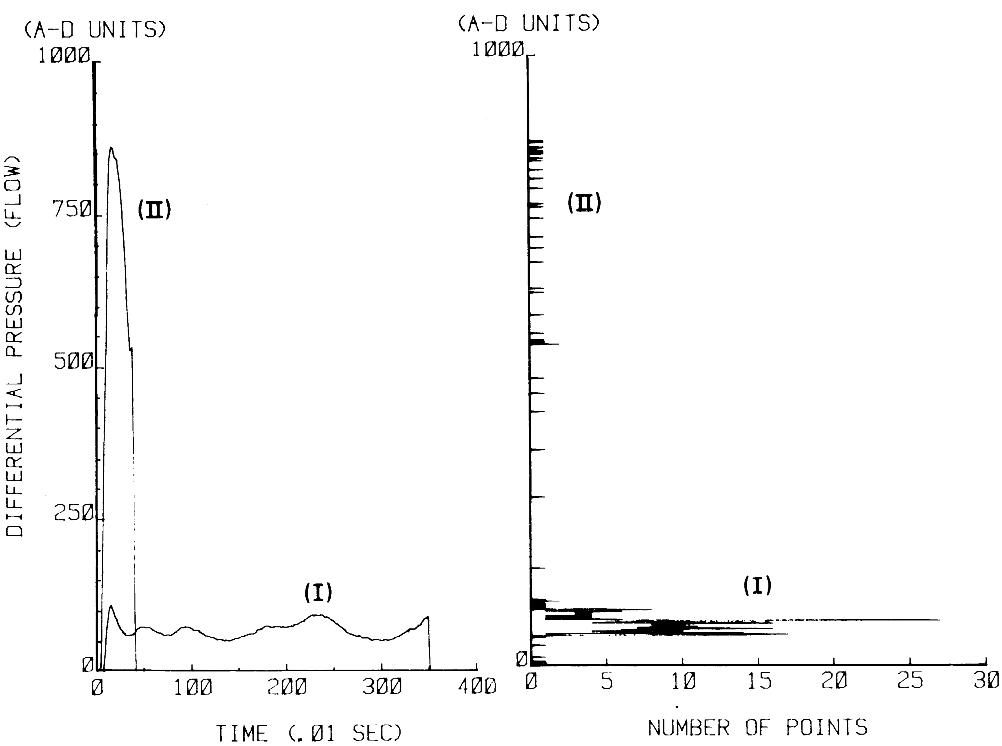

FIG. 2. Pressure-time curves (*left*) and histograms (*right*) of 2 syringe strokes. *Stroke I* took 3.5 s and *stroke II* took less than 0.5 s. Fast stroke (II) has pressure points distributed on *histogram*, whereas slow stroke (I) is confined to a smaller pressure range (*left*). For only 2 strokes, many pressure values do not have any pressure points associated with them.

determined from pressure and conductance as shown in *Eq. 1*, utilizing the fact that flow equals pressure times conductance.

Volume = $\int$ flow$\cdot$dt = Σ(flow$\cdot$sampling interval) = (Σ flow)$\cdot$sampling interval.

Since flow = pressure$\cdot$conductance

volume

= [Σ (pressure$\cdot$conductance)]$\cdot$sampling interval (*1*)

If the volume is 3 liters and conductance values are the same for all three pressure values within a given stroke, *Eq. 1* becomes

volume = 3 (liters)

$$= \{\Sigma[\text{pressure(ADU)}\cdot K_i]\}\cdot 0.01(\text{s}) \quad (2)$$

$$= (\Sigma\ \text{pressure})\cdot K_i \cdot 0.01$$

where K_i is the constant gross conductance value for *stroke i*. Therefore

$$K_i = 3/[(\Sigma\ \text{pressure})\cdot 0.01]$$

$$= 300/(\Sigma\ \text{pressure})[\text{l}/(\text{s}\cdot\text{ADU})]$$

Then for *stroke 1*

$$K_1 = 300/(1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 2 + 2 + 2 + 2 + 3 + 3)$$

$$= 300/(11\cdot 1 + 4\cdot 2 + 2\cdot 3)$$

$$= 12.00[\text{l}/(\text{s}\cdot\text{ADU})]$$

For *stroke 2*

$$K_2 = 300/(2\cdot 1 + 4\cdot 2 + 4\cdot 3)$$

$$= 13.64[\text{l}/(\text{s}\cdot\text{ADU})]$$

After the gross conductance values for all strokes have been determined (12.00 for *stroke 1* and 13.64 for *stroke 2*), conductance values for each pressure value may be calculated. For the pressure value of 1 ADU, 11 points from *stroke 1* indicate the conductance is 12.00, and 2 points from *stroke 2* indicate the conductance is 13.64. When the weighted-averaging technique is applied, the conductance value corresponding to 1 ADU pressure value is determined as follows

$$\text{conductance}_{\text{ADU}_1} = (12.00 \cdot 11 + 13.64 \cdot 2)/(11 + 2)$$
$$= 12.25[\text{l}/(\text{s} \cdot \text{ADU})]$$

Similarly

$$\text{conductance}_{\text{ADU}_2} = (12.00 \cdot 4 + 13.64 \cdot 4)/(4 + 4)$$
$$= 12.82[\text{l}/(\text{s} \cdot \text{ADU})]$$
$$\text{conductance}_{\text{ADU}_3} = (12.00 \cdot 2 + 13.64 \cdot 4)/(2 + 4)$$
$$= 13.09[\text{l}/(\text{s} \cdot \text{ADU})]$$

Therefore, the conductance values are 12.25, 12.82, and 13.09 l/(s·ADU) for the pressure values of 1, 2, and 3 ADU.

Since conductance values differ slightly even for neighboring pressure values, the assumption of constant conductance values for all pressure values within a given stroke is not correct. Therefore we developed a more elaborate approach that uses conductance values from a previous calibration to determine the current conductance values. Within a given *stroke i*, all current conductance values are assumed to deviate from their previous values by a small factor, e_i. From *Eq. 1*

$$\text{volume} = 3 \text{ (liters)}$$
$$= \{\Sigma[\text{pressure} \cdot (\text{previous conductance} \cdot e_i)]\} \cdot 0.01 \quad (3)$$
$$= [\Sigma(\text{pressure} \cdot \text{previous conductance})] \cdot e_i \cdot 0.01$$

where e_i is the correction factor for *stroke i*. Thus

$$e_i = 300/[\Sigma(\text{pressure} \cdot \text{previous conductance})]$$

If the previous conductance values are 12.25, 12.82, and 13.09 l/(s·ADU) for pressure of 1, 2, and 3 ADU, respectively, and the two strokes have the same configurations as in the last example, then the correction factor for *stroke 1* is

$$e_1 = 300/[11 \cdot (12.25 \cdot 1) + 4 \cdot (12.82 \cdot 2) + 2 \cdot (13.09 \cdot 3)]$$
$$= 0.9498$$

For *stroke 2*,

$$e_2 = 300/(2 \cdot 12.25 \cdot 1 + 4 \cdot 12.82 \cdot 2 + 4 \cdot 13.09 \cdot 3)$$
$$= 1.0558$$

Again, the weighted averaging technique is used to ascertain the correction factors for all pressure values

$$e_{\text{ADU}_1} = (0.9498 \cdot 11 + 1.0558 \cdot 2)/(11 + 2)$$
$$= 0.9661$$
$$e_{\text{ADU}_2} = (0.9498 \cdot 4 + 1.0558 \cdot 4)/(4 + 4)$$
$$= 1.0028$$
$$e_{\text{ADU}_3} = (0.9498 \cdot 2 + 1.0558 \cdot 4)/(2 + 4)$$
$$= 1.0205$$

Finally, conductance values are determined as follows

$$\text{conductance}_{\text{ADU}_1} = e_{\text{ADU}_1} \cdot \text{previous conductance}_{\text{ADU}_1}$$
$$= 0.9661 \cdot 12.25$$
$$= 11.83[\text{l}/(\text{s} \cdot \text{ADU})]$$
$$\text{conductance}_{\text{ADU}_2} = e_{\text{ADU}_2} \cdot \text{previous conductance}_{\text{ADU}_2}$$
$$= 1.0028 \cdot 12.82$$
$$= 12.86[\text{l}/(\text{s} \cdot \text{ADU})]$$
$$\text{conductance}_{\text{ADU}_3} = e_{\text{ADU}_3} \cdot \text{previous conductance}_{\text{ADU}_3}$$
$$= 1.0205 \cdot 13.09$$
$$= 13.36[\text{l}/(\text{s} \cdot \text{ADU})]$$

Once these conductance values have been calculated, the system can be used to determine breath volume. For example, if a given breath consists of 5 points of 1 ADU, 2 points of 2 ADU, and 1 point of 3 ADU pressure values, the breath volume is calculated from *Eq. 1* as

$$\text{breath volume}$$
$$= [\Sigma(\text{pressure} \cdot \text{conductance})] \cdot \text{sampling interval}$$
$$= (5 \cdot 11.83 \cdot 1 + 2 \cdot 12.86 \cdot 2 + 1 \cdot 13.36 \cdot 3) \cdot 0.01$$
$$= 1.5067 \text{ (liters)}$$

The algorithm of this weighted-averaging technique is found in the APPENDIX.

RESULTS AND DISCUSSION

Previous investigators (3, 6) have evaluated the nonlinearity of flowmeters by examining the flow-pressure curve. The use of conductance (flow/pressure) vs. pressure, however, appears to be a more sensitive method for assessing nonlinearity. To confirm this, we have included typical data, provided by the manufacturer, for the Fleisch pneumotachometer (Table 1). Figure 3 shows the data plotted for flow vs. pressure, and Fig. 4 shows the same data plotted for conductance vs. pressure. Although the flow-pressure curve (Fig. 3) appears to be linear, the conductance-pressure curve (Fig. 4) based on the same data indicates a difference of 7.46% between the minimum conductance value (47.14 $\text{l} \cdot \text{min}^{-1} \cdot \text{mmH}_2\text{O}^{-1}$) and the maximum conductance value (50.94) $\text{l} \cdot \text{min}^{-1} \cdot \text{mmH}_2\text{O}^{-1}$). If the pneumotachometer had been linear, the conductance would have been constant and the conductance-pressure curve (Fig. 4) would have been a straight horizontal line.

The conductance of the Fleisch pneumotachometer, sometimes referred to as a "conversion factor", has been determined using different techniques (7, 11, 12). If the flow of a pneumotachometer, with characteristics as seen in Fig. 4, is calculated by multiplying the measured pressure value by a fixed conversion factor (11), the absolute error due to nonlinearity will be about ±3.73% (=7.46%/2). On the other hand, if the flow is derived from the equation "flow = $aV + bV^2$", where V is pressure (7, 12), the conversion factors (flow/V) will be "flow/V = $a + bV$". This is equivalent to approximating the conductance-pressure curve by using a straight line. If the least-square-error criterion is used to calculate the

TABLE 1. *Typical data of Fleisch no. 3 pneumotachometers*

Pressure, mmH_2O	Flow		Conductance, $l \cdot min^{-1} \cdot mmH_2O^{-1}$
	l/s	l/min	
10	8.246	494.76	49.48
9	7.500	450.00	50.00
8	6.720	403.22	50.40
7	5.891	353.46	50.49
6	5.070	304.17	50.70
5	4.245	254.70	50.94
4	3.377	202.63	50.66
3	2.521	151.28	50.43
2	1.658	99.45	49.73
1	0.802	48.15	48.15
0.5	0.393	23.57	47.14

Pressure and flow in l/s data were provided by the manufacturer (9). Flow in l/min and conductance values were calculated.

coefficients a and b, then the absolute error due to the straight-line approximation will be about ±2.5% over the range of 0–7 mmH_2O (linear range specified by the manufacturer).

The weighted averaging method described in this paper utilized a conductance table based on multiple strokes of the calibration syringe. For each measured pressure value, a conductance value is located by table look up. The flow is then calculated by multiplying the pressure by the corresponding conductance value. The accuracy of the flow depends on the accuracy of the conductance value, which improves as the number of strokes increases. Figure 5 shows a measured volume distribution for 100 strokes of a calibrated syringe (2,992 ml). The conductance characteristics were determined earlier with 100 strokes of the same syringe. The mean measured volume is 2,992 ± 7.8 (SD) ml, and the minimum and maximum

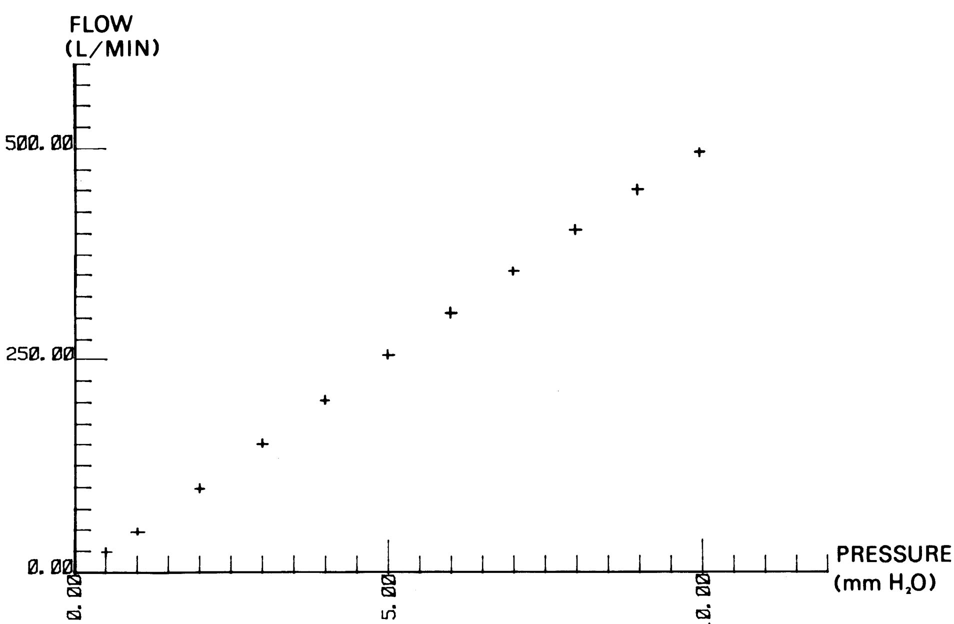

FIG. 3. Flow-pressure curve of typical data of Fleisch no. 3 pneumotachometer provided by manfuacturer (see Table 1).

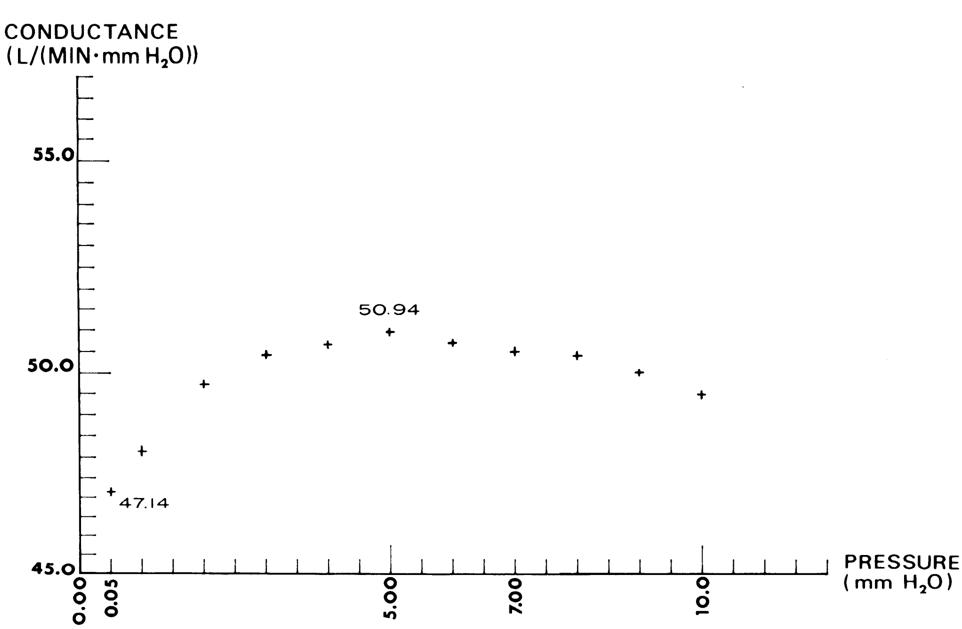

FIG. 4. Conductance-pressure curve of typical data of Fleisch no. 3 pneumotachometer provided by manufacturer. Note that at low and high flows (pressures), conductance is lower than at mid-flows (pressures).

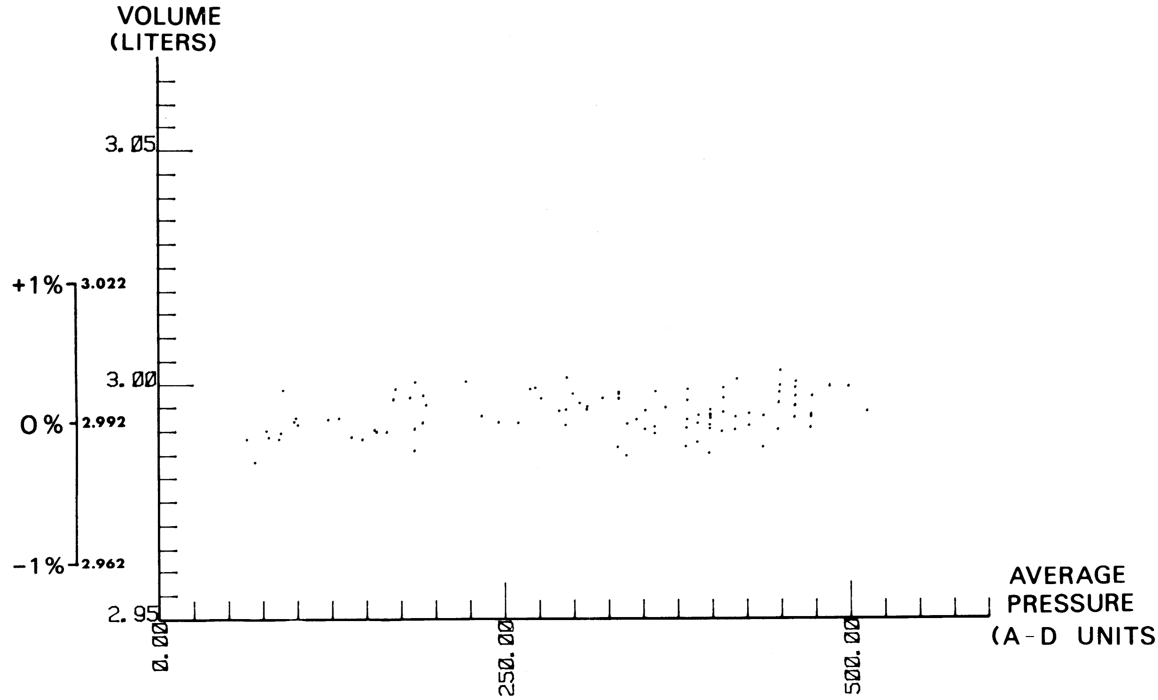

FIG. 5. Volume distribution of 100 strokes of calibrated 2,992-ml syringe. Measured volumes are 2,993 ± 7.8 ml (mean ± SD), with minimum of 2,884 and maximum of 3,003 ml.

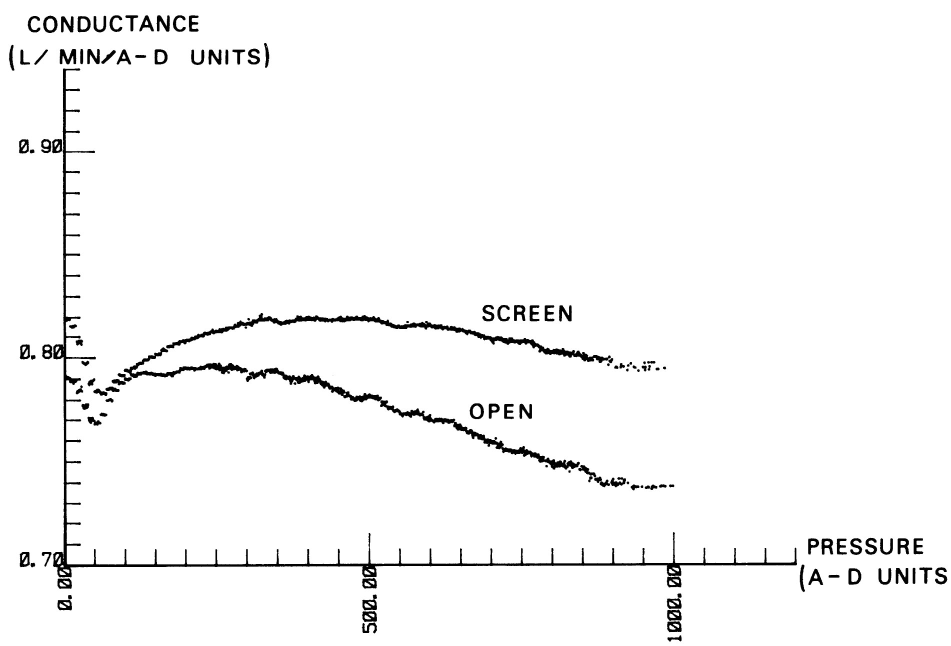

FIG. 6. Conductance characteristics of Fleisch no. 3 pneumotachometer, with wide-open upstream geometry (*open curve*) and with manufacturer's metal screen on upstream side (*screen curve*). Note that *screen curve* is flatter than *open curve*.

values are 2,984 and 3,003 ml, respectively. The absolute error is less than ±0.5%. It should be noted that the multiple strokes of a syringe must be of different velocities. Several slow strokes are essential for the accuracy of low flows.

We agree with data by Finucane et al. (3), that the upstream geometry (inspired side) of the Fleisch pneumotachometer vitally affects its linearity. Figure 6 shows the conductance characteristics of the Fleisch no. 3 pneumotachometer, which are derived from the weighted-averaging technique. The open curve was derived from a pneumotachometer with a wide-open upstream side, whereas the screen curve was determined from the same pneumotachometer with the manufacturer's metal cone screen upstream. The metal cone screen provides an even flow pattern by decreasing the velocity at the center, thus decreasing the degree of turbulence. As a result, the pneumotachometer with the metal screen has a lower resistance for fast flows and provides flatter conductance characteristics.

Curves in Fig. 6 were determined from 100 strokes of the syringe. With fewer strokes, the conductance curve is slightly less convergent. However, the volume accuracy (±1%) for 50 strokes, for example, is satisfactory for clinical purposes. Although the conductance characteristics of the high-flow portion of the Fleisch no. 3 pneumotachometer remains the same, the low-flow portion (<50 l/min) may change in shape.

In conclusion it should be pointed out that neither Fleisch nor other pneumotachometers are absolutely lin-

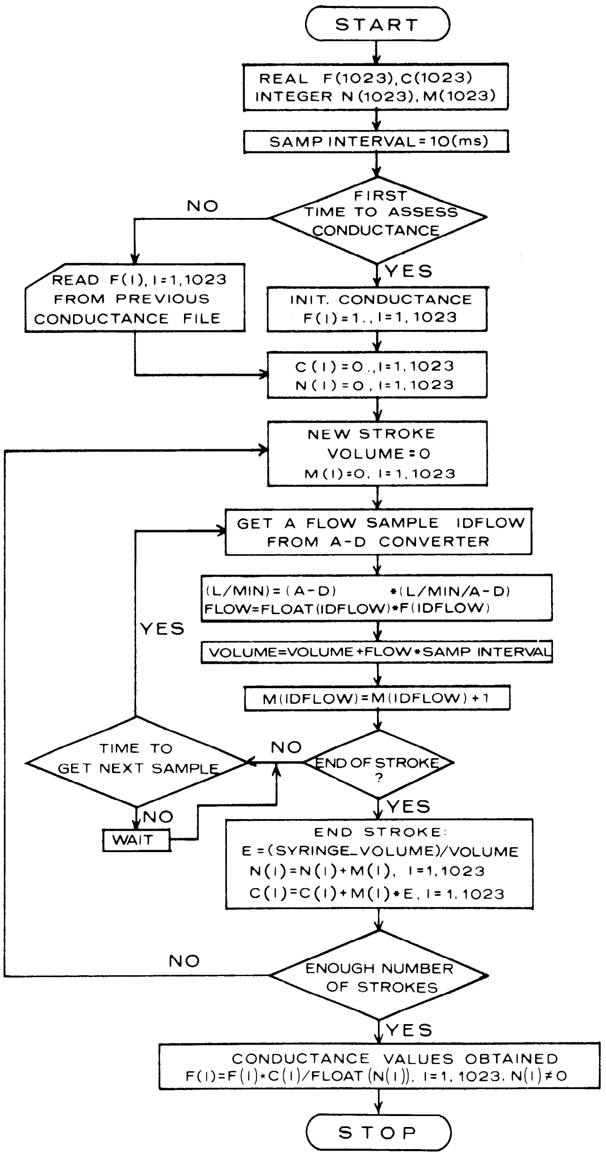

FIG. 7. Flow chart of weighted-averaging technique to determine conductance.

ear. The nonlinearity of these devices is best demonstrated by looking at conductance vs. pressure characteristics as mentioned earlier. Our results show that linear or quadratic fitting of the pressure-flow characteristics do not provide accurate correction. Research and clinical users of pneumotachometers frequently require flow and volume accuracies of at least ±1%. With this in mind we have developed a computerized weighted-average method that will achieve the required accuracy.

APPENDIX

Calibration Algorithm

The algorithm used to determine the conductance characteristics of a flowmeter is flow charted in Fig. 7. Four arrays are required: f(i), c(i), n(i), and m(i), each with $i = 1$ to 1,023. Array f(i), initialized with previously determined conductance values (or 1.0) when calibration begins, represents the conductance (flow/pressure). Both arrays c(i) and n(i) are initialized to 0 when the calibration begins. Array c(i) accumulates correction factors for the conductance values. Array n(i) counts the number of pressure points with an A/D value of i accumulated over all strokes of the syringe. Array m(i), initialized to 0 at the beginning of each stroke, counts the number of pressure points with A/D values of i.

During each stroke, points of various A/D values are obtained from the flow measuring device. A measured volume of the stroke is obtained by numerically integrating the product of these A/D values with the corresponding conductance values (with respect to time). A correction factor, e, for the stroke is calculated by dividing the "actual" volume by the measured volume.

At the end of the stroke, m(i) is calculated, the number of points in this stroke having an A/D value of i. Array c(i), where $i = 1$ to 1,023, is incremented by the product of m(i) and the correction factor e. Array n(i) is also incremented by m(i), where $i = 1$ to 1,023.

After the predetermined number of strokes is processed, a new array of conductance values is calculated from f(i)·c(i)/n(i), where $i = 1$ to 1,023 and n(i) is not equal to 0. For A/D values with n(i) = 0, the average of the neighboring existing conductance values is used. The new array of conductance values will then be used to correct the nonlinearity of the flow-measuring device at each point.

Our system defines the size of the conductance array f(i) as 103, instead of 1,023. Each conductance value then corresponds to 10 A/D pressure values. Since pressure values in the range of 10 A/D units (representing a range of about 6 l/min flow) have close corresponding conductance values, the error introduced by the "segmentation" is negligible and 920 real words of computer memory are saved.

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