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TECHNICAL NOTE

The accuracy of dry gas meters at continuous and sinusoidal flows

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The accuracy of dry gas meters at continuous and sinusoidal flows. J.D. Hart, R.T. Withers, A.H. Ilsley.

ABSTRACT: Dry gas meters are used in physiology laboratories to measure minute ventilation. The accuracy of these meters must be known since an error, of for instance 5%, affects the subsequent calculations for oxygen consumption by the same amount.

Two precalibrated DTM-325 dry gas meters (American Meter Co., Philadelphia, PA, USA) were therefore tested for accuracy against a 350 *l* Collins chain-compensated gasometer.

Provided that at least 25 *l* was passed per measurement then: a. continuous flows (air saturated with water vapour) between 60 and 150 $l \cdot min^{-1}$ were measured with an error of <1%; and b. sinusoidal flows (ambient air) between 8 and 100 $l \cdot min^{-1}$ were misread by <1% and the error was still within 2% at 140 $l \cdot min^{-1}$.

It may, therefore, be concluded that the two precalibrated dry gas meters studied are valid volume measuring devices.

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The measurement of oxygen consumption ($\dot{V}O_2$) is a basic technique in exercise physiology laboratories. The importance of the volume measuring device is highlighted by the fact that if it under- or overreads by 5% then the $\dot{V}O_2$ will be in error by an identical amount. The aims of this study were therefore to: 1. Determine the accuracy of calibrated dry gas meters at constant flow rates. This was done because the traditional method of measuring $\dot{V}O_2$ is to collect the expirate in a Douglas Bag [1] from which a small aliquot is removed, dried and analysed for percentage O_2 and percentage CO_2. A vacuum pump then draws the bag's contents through a gas meter at a constant flow rate. 2. Check the accuracy of dry gas meters, which have been calibrated at continuous flow rates, at various combinations of tidal volume (VT) and frequency (*f*) spanning the physiological range from rest to maximum exercise. This mimics automated and semi-automated $\dot{V}O_2$ systems where the dry gas meter is placed on the inspiratory limb [1, 2]. Such a position avoids the corrosion and volume displacement caused by the condensation within the meter of water vapour from the expirate.

Methods

Meter calibration

Two DTM-325 (Dry Test Meter - 325 $ft^3 \cdot hr^{-1}$) dry gas meters (American Meter Co., Philadelphia, PA, USA) were tested against the reference standard of a 350 *l* Collins chain-compensated gasometer (Warren E. Collins Inc., Braintree, MA, USA) which was checked for an accurate cross-sectional volume throughout its elevation (1 mm = 324.4 ml) using 1 *l* (P.K. Morgan, Rainham, Kent, UK) and 3.92 *l* (M20, SRL Medical Inc., Dayton, OH, USA) calibration syringes. The volumes of these syringes were authenticated against a 10 *l* Stead-Wells spirometer (Warren E. Collins Inc., Braintree, MA, USA). The axis of rotation of the pointer on the dry gas meter's dial was attached to an optical shaft encoder model EC81-1000-S (Disc Instruments Inc., Costa Mesa, CA, USA). A digital readout displayed the volume to the nearest 0.01 *l*. The initial connection of the shaft encoder caused the meters to underread by 4–5% due to the additional rotational inertia. The two meters with shaft encoders attached were calibrated to read within ±1% of the minute volume of two continuous reference flows (60 and 150 $l \cdot min^{-1}$) *via* alterations to the internal mechanism [3].

Alinearity of meter diaphragm

The alinearity of each dry gas meter's bellows within a revolution of the pointer on the dial was examined by recording the volume displayed after each of 60 consecutive 1 *l* boluses from a calibration syringe.

Continuous flow test circuit

The calibration circuit, which mimicked the Douglas Bag method, was: water vapour saturated atmospheric air in 350 *l* gasometer, approximately 0.8 m of 3.8 cm ID corrugated plastic tubing, inlet of gas meter, outlet of gas meter and approximately 0.8 m of 3.8 cm ID corrugated plastic tubing to the vacuum pump. The pressure drop across the meter was measured by an incline plane manometer. Tests were conducted with flow rates of 5–200 $l \cdot min^{-1}$. The badged capacity, which is the manufacturer's recommended maximum flow rate, is 325 $ft^3 \cdot h^{-1}$ or 153 $l \cdot min^{-1}$. A ceiling of 200 $l \cdot min^{-1}$ was placed on the continuous flow tests to examine meter performance over as wide a flow range as possible. The temperatures of the gas in the bell and the meter were monitored during all tests [4].

Sinusoidal flow test circuit

The calibration circuit for the sinusoidal flow tests was: atmospheric air into inlet of dry gas meter, outlet of dry gas meter, approximately 0.8 m of 3.8 cm ID corrugated plastic tubing, inlet port of R2700 respiratory valve (Hans Rudolph, Kansas City, MO, USA), sinusoidal waveform generator (two of different capacities were constructed by our Department of Biomedical Engineering) connected to the respiratory valve's mouthpiece and approximately 0.8 m of 3.8 cm ID corrugated plastic tubing from the respiratory valve's outlet to the 350 *l* gasometer. The pressure drop across the meter was again measured by an incline plane manometer. A dew point hygrometer model 880 (EG & G International Inc., New York, NY, USA) was used to calculate the volume of water vapour added to the injected air by the water jacket of the gasometer bell. This volume was subtracted to obtain the actual reference volume. Resting respiration was simulated by passing 50 *l* for one trial of all combinations of 0.4, 0.6, 0.8, 1.0 *l* tidal volumes and 8, 12, 16, 20 $br \cdot min^{-1}$. Exercise flow waveforms were also simulated by passing 300 *l* for one trial of all combinations of 1.0, 1.5, 2.1, 2.6, 3.1 *l* tidal volumes and 15, 25, 35, 45, 55, 65 $br \cdot min^{-1}$. The temperatures of the gas in the bell and the meter were monitored during all tests [4]. There were no leaks in the Hans Rudolph respiratory valve due to gas entrainment for any of the flow waveforms [5].

Results

Reference standard

The standard deviation of both sets of cross-sectional volumes (0.3%) was equivalent to the visual discrimination of the bell elevation (0.1 mm), indicating that the bell had a highly uniform cross-sectional volume throughout its elevation. The effectiveness of the chain compensation in maintaining an internal bell gas pressure equal to that of the atmosphere was confirmed by connecting a water manometer to the gas sampling petcock during bell filling and emptying (maximum pressure-induced volume change of 0.01%).

Accuracy

After the two meters had been precalibrated to read continuous flows of 60 and 150 $l \cdot min^{-1}$ to within 1% error, they were shown to maintain this degree of accuracy for intervening continuous flows (figs 1 and 2).

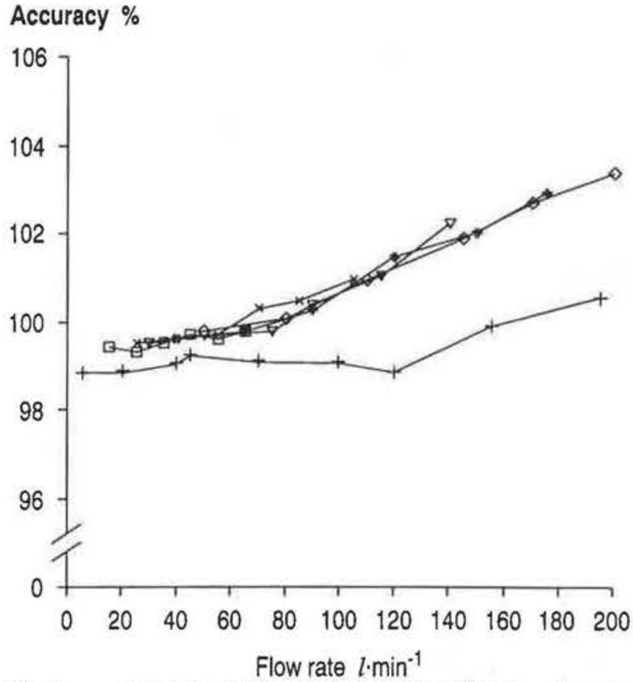

Fig. 1. – Accuracy of dry gas meter A at continuous and exercising sinusoidal flows. % accuracy=(gas meter volume/Collins gasometer volume) × 100. —+— : continuous flows; —□— : 1.0 *l* at 15–65 $br \cdot min^{-1}$; —✶—: 1.5 *l* at 15–65 $br \cdot min^{-1}$; —▽—: 2.1 *l* at 15–65 $br \cdot min^{-1}$; —#—: 2.6 *l* at 15–65 $br \cdot min^{-1}$; —◇—: 3.1 *l* at 15–65 $br \cdot min^{-1}$.

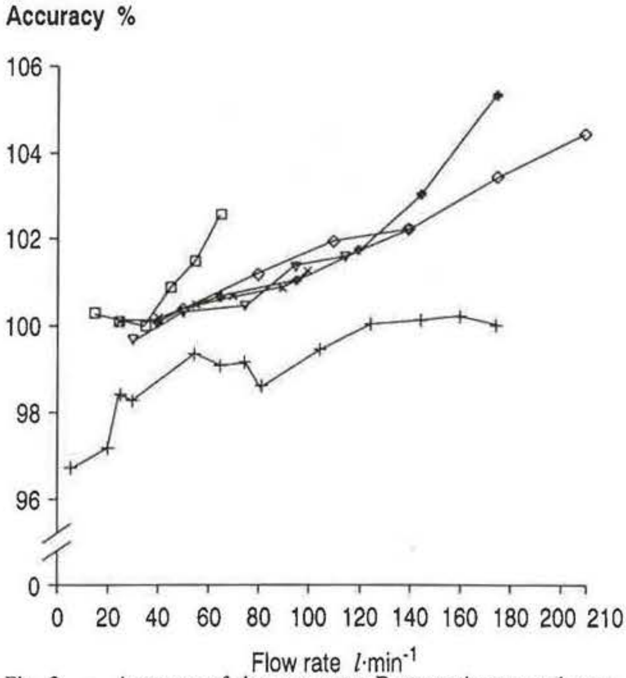

Fig. 2. – Accuracy of dry gas meter B at continuous and exercising sinusoidal flows. % accuracy=(gas meter volume/Collins gasometer volume) × 100. For key to symbols see legend to figure 1.

However, one meter began to substantially underread at continuous flows <60 $l \cdot min^{-1}$ (fig. 2). Both meters recorded mean sinusoidal waveform flows from 8 to 100 $l \cdot min^{-1}$ to within 1% error (figs 1–4). Sinusoidal flows from 4 to 140 $l \cdot min^{-1}$ were measured to ±2%.

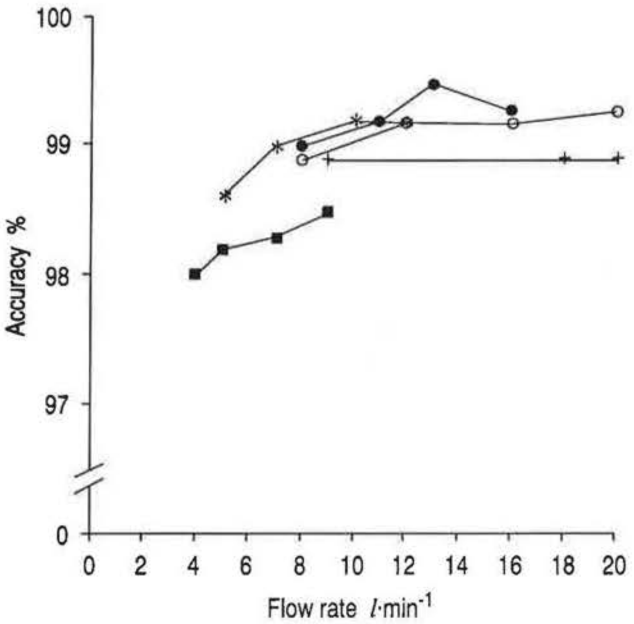

Fig. 3. – Accuracy of dry gas meter A at continuous and resting sinusoidal flows. % accuracy=(gas meter volume/Collins gasometer volume) × 100. —+— : continuous flows; —■— : 0.4 l at 8–20 $br \cdot min^{-1}$; —*— : 0.6 l at 8–20 $br \cdot min^{-1}$; —●— : 0.8 l at 8–20 $br \cdot min^{-1}$; —○— : 1.0 l at 8–20 $br \cdot min^{-1}$.

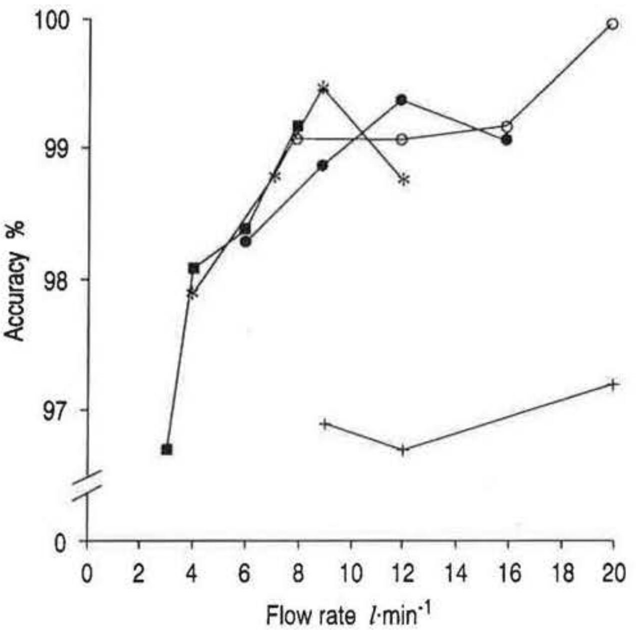

Fig. 4. – Accuracy of dry gas meter B at continuous and resting sinusoidal flows. % accuracy=(gas meter volume/Collins gasometer volume) × 100. For key to symbols see legend to figure 3.

Alinearity of diaphragm

The 60 one litre boluses were read with an error of between -24 to +16% ($\bar{x}$=0.99 l, SD = 0.11 l) for meter A and between -27 to +23% ($\bar{x}$=1.00 l, SD=0.11 l) for meter B. The error varied with the position of each meter's diaphragm in its filling-emptying cycle and was not coincident with any one point on the 10 l dial.

Pressure differential across meter

The resistances to gas flow over just the meters were similar for both measuring devices and were about 0.09 kPa (0.9 cmH_2O) and 0.17 kPa (1.7 cmH_2O) for continuous (200 $l \cdot min^{-1}$) and sinusoidal flows (3.1 l × 65 $br \cdot min^{-1}$), respectively.

Discussion

This study agrees with other reports which have found significant alinearity in the gas volume measured by a dry gas meter depending upon where the gas is passed in the expansion range of the bellows [2, 6, 7]. As at least 25 l must be passed per measurement to ensure an alinearity-induced error of <1%, the dry gas meter is unsuitable for measuring small volumes (25% alinearity of 1 l = 250 ml absolute error, 250 ml/25 l = 1% relative error) [5].

Gas volume measurement error of 3 [8] to 5% [9] permits the monitoring of disease course and the clinical assessment of a subject's respiratory function. However, <2% error is required for respiratory research purposes [10, 11] and when monitoring the small functional capacity changes due to training in the athlete.

We have shown that 100% accuracy at the 153 $l \cdot min^{-1}$ badged capacity is achievable with continuous flows. The manufacturer specifies a maximum error of 1% at this flow rate. At the flow rates (50–100 $l \cdot min^{-1}$) used during the Douglas Bag measurement technique, the meters are well within the 2% error requirements for research purposes. Furthermore, the pressure differential across each meter had a negligible effect on the accuracy of the measured gas volume and demonstrated the meter's low resistance to flow.

The dry gas meters tended to overread sinusoidal flows by 0.5–5% compared with the reading of the same volume passed as a continuous flow (4–200 $l \cdot min^{-1}$). The difference increased steadily with the mean flow rate, but was <2% for flows which were <140 $l \cdot min^{-1}$. The absolute accuracy of the meters ranged from 99.5–104% for sinusoidal flows between 30–200 $l \cdot min^{-1}$. This decreased to within 2% error for flows <140 $l \cdot min^{-1}$ and to within 1% for flows between 8–100 $l \cdot min^{-1}$. Each meter's absolute accuracy, and its sinusoidal performance with respect to the continuous flow waveform used during calibration, indicates they can be used for determining sinusoidal waveform gas volumes during physiological studies, provided that the flow rate of the inspired ambient air is <140 $l \cdot min^{-1}$.

This is approximately 152 $l\cdot min^{-1}$ at body temperature, ambient pressure and saturated with water vapour (BTPS).

The combination of tidal volume and respiratory frequency used to deliver a sinusoidal minute volume had very little effect upon the meter's accuracy over the physiological range of minute ventilation tested (1% variation at flow rates less than the badged capacity). The effect of a skewed waveform, as occurs during low physiological flow rates [12], is unknown.

The pressure differential across the meter during sinusoidal flows was evaluated during all waveforms but inertia of the manometer's water column prevented accurate measurement. However, the previously quoted continuous flow pressure differentials confirm an overall low resistance to gas flow.

In summary, we found that, if the American Meter Co. DTM-325 dry gas meter is calibrated in accordance with the manufacturer's instructions, it is an acceptable volume measurement device of continuous and sinusoidal gas flows. The only proviso is that at least 25 l is passed per measurement to negate the inaccuracy caused by the alinearity of the meter's diaphragm through a measurement cycle.

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