Turbine flowmeter vs. Fleisch pneumotachometer: a comparative study for exercise testing

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YEH, MINKEN P., TED D. ADAMS, REED M. GARDNER, AND FRANK G. YANOWITZ. *Turbine flowmeter vs. Fleisch pneumotachometer: a comparative study for exercise testing.* J. Appl. Physiol. 63(3): 1289–1295, 1987.—The purpose of this study was to investigate the characteristics of a newly developed turbine flowmeter (Alpha Technologies, model VMM-2) for use in an exercise testing system by comparing its measurement of expiratory flow ($\dot{V}E$), O_2 uptake ($\dot{V}O_2$), and CO_2 output ($\dot{V}CO_2$) with the Fleisch pneumotachometer. An IBM PC/AT-based breath-by-breath system was developed, with turbine flowmeter and dual-Fleisch pneumotachometers connected in series. A normal subject was tested twice at rest, 100-W, and 175-W of exercise. Expired gas of 24–32 breaths was collected in a Douglas bag. $\dot{V}E$ was within 4% accuracy for both flowmeter systems. The Fleisch pneumotachometer system had 5% accuracy for $\dot{V}O_2$ and $\dot{V}CO_2$ at rest and exercise. The turbine flowmeter system had up to 20% error for $\dot{V}O_2$ and $\dot{V}CO_2$ at rest. Errors decreased as work load increased. Visual observations of the flow curves revealed the turbine signal always lagged the Fleisch signal at the beginning of inspiration or expiration. At the end of inspiration or expiration, the turbine signal continued after the Fleisch signal had returned to zero. The "lag-before-start" and "spin-after-stop" effects of the turbine flowmeter resulted in larger than acceptable error for the $\dot{V}O_2$ and $\dot{V}CO_2$ measurements at low flow rates.

personal computer; breath-by-breath exercise studies; turbine hysteresis

FOR MANY YEARS, the Fleisch pneumotachometer has been widely used in the measurement of flow for breath-by-breath exercise studies. The Fleisch pneumotachometer, however, is sensitive to gas composition variation and temperature change (5, 7). Recently, a turbine flowmeter was developed by Alpha Technologies (Laguna Hills, CA). This new flow device has a lightweight pickup assembly (20 mg) and a low dead space (70 ml). In addition, the turbine flowmeter has been reported to be insensitive to a gas composition change of room air to pure O_2 and unaffected by water vapor and temperature (3). Initial attempts in our laboratory to use the turbine flowmeter in a breath-by-breath system, however, indicated large errors in the measurement of O_2 consumption ($\dot{V}O_2$) and CO_2 production ($\dot{V}CO_2$). Therefore the purpose of this study was to investigate the characteristics of this new turbine flowmeter by comparing its measurement of expiratory flow ($\dot{V}E$), $\dot{V}O_2$, and $\dot{V}CO_2$ with the Fleisch pneumotachometer at various exercise conditions.

METHODS

A computerized breath-by-breath system using an IBM PC/AT computer and an off-the-shelf data acquisition system was developed (Fig. 1). The system includes *1)* MetraByte DASH-16 analog-to-digital (A/D) interface, *2)* MetraByte CTM-05 counter-timer interface; *3)* Perkin-Elmer MGA-1100 mass spectrometer, *4)* Alpha Technologies VMM-2 ventilation measurement module, and *5)* a dual-flowmeter scheme using two Fleisch no. 3 pneumotachometers, Validyne DP-45 pressure transducers, and Validyne CD-12 carrier demodulators. The expiratory Fleisch pneumotachometer was heated at 32°C. The Alpha Technologies VMM-2 contains an electronic processing module as well as a digital volume transducer. The digital volume transducer is composed of a pickup assembly and a volume cartridge. The electronic processing module of the VMM-2 incorporates a "pulse-injection" technique to compensate for the nonlinearity at low flow rates. It also provides separate inspiratory and expiratory flow signals and therefore is functionally similar to the dual-flowmeter data acquisition system.

The DASH-16 data acquisition board, with 12-bit A/D resolution, was configured with eight-channel differential inputs. Two channels of the CTM-05 digital counter board were used to accumulate digital pulses from the VMM-2 for turbine inspiratory and expiratory flows. Each digital pulse from the VMM-2 measures ~2 ml of volume. Both A/D and counter data were sampled at a 100-Hz rate. The system calculated $\dot{V}E$, $\dot{V}O_2$, and $\dot{V}CO_2$ breath by breath and with a four-breath average. Haldane transformation (8) was applied in the calculation of $\dot{V}E$ by assuming the amount of N_2 inspired was equal to that expired over a four-breath period. Both the breath-by-breath and four-breath data were saved on disk files and could be printed or plotted, operating similarly to a system previously developed using Data General's Nova 4 minicomputer (10). In addition, digitized A/D and digital counter signals were recorded on the hard disk while the exercise test was in progress. After the test, the recorded digital signals could be played back for examination or reprocessing. To test the differences between the turbine flowmeter and the dual-Fleisch pneumotachometers, the flowmeters were connected with a Hans-Rudolph two-way valve (model 2700, large), as shown in Fig. 2, so that the flowmeters measured the flow signals simultaneously during the test.

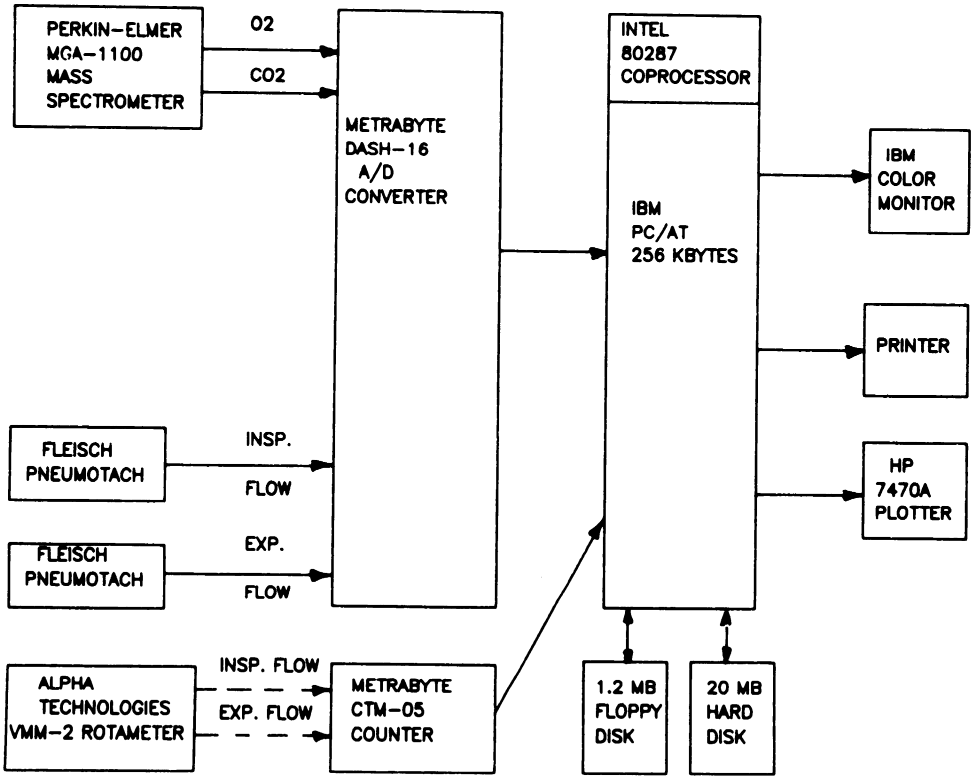

FIG. 1. Block diagram (hardware configuration) of the IBM PC/AT computer-based breath-by-breath exercise test system.

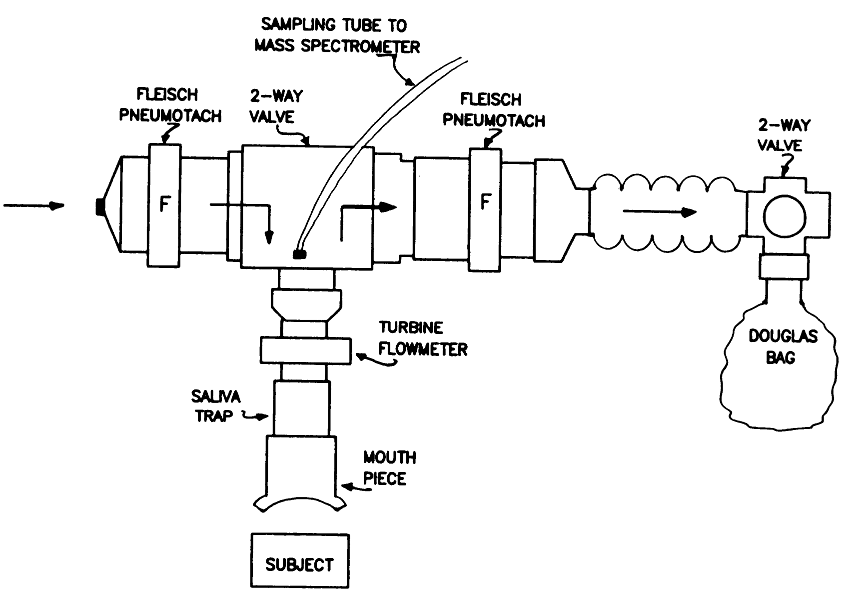

FIG. 2. Arrangement of Fleisch pneumotachometers, turbine flowmeter, two-way valve, and gas sampling catheter.

The breath-by-breath system was calibrated with three calibration procedures: *1*) calibration of both flowmeter characteristics using a weighted average method with a calibrated 3-liter syringe (9); *2*) determination of the gas analyzer transport delay and response time using a solenoid-controlled valve and a pressurized balloon filled with expired gas (1, 6); and *3*) determination of the A/D conversion factors for the O_2 and CO_2 using room air and a standard physiological gas (16% O_2-5% CO_2). The O_2 and CO_2 conversion factors were later used to convert the gas signals to concentrations for gas exchange calculations. The calibration of both flowmeters was made while the mass spectrometer was sampling gas, to duplicate actual testing situations.

Four studies were conducted to measure the flow signals at various flow rates. A normal human subject was tested breath by breath twice at rest (*tests 30* and *31*), during 100-W bicycle ergometer exercise (*tests 32* and *33*), and during 175-W exercise (*tests 40* and *41*). The two tests for each work load were conducted within 1 h. The fourth test included a rapid flush of expired gas from a pressurized balloon connected to the solenoid-controlled valve.

For the human studies (rest, 100-W exercise, and 175-W exercise), expired gas was also collected in a Douglas bag for 24–32 breaths. The concentration of expired gas in the bag was later measured with the Perkin-Elmer MGA-1100 mass spectrometer. The volume was mea-

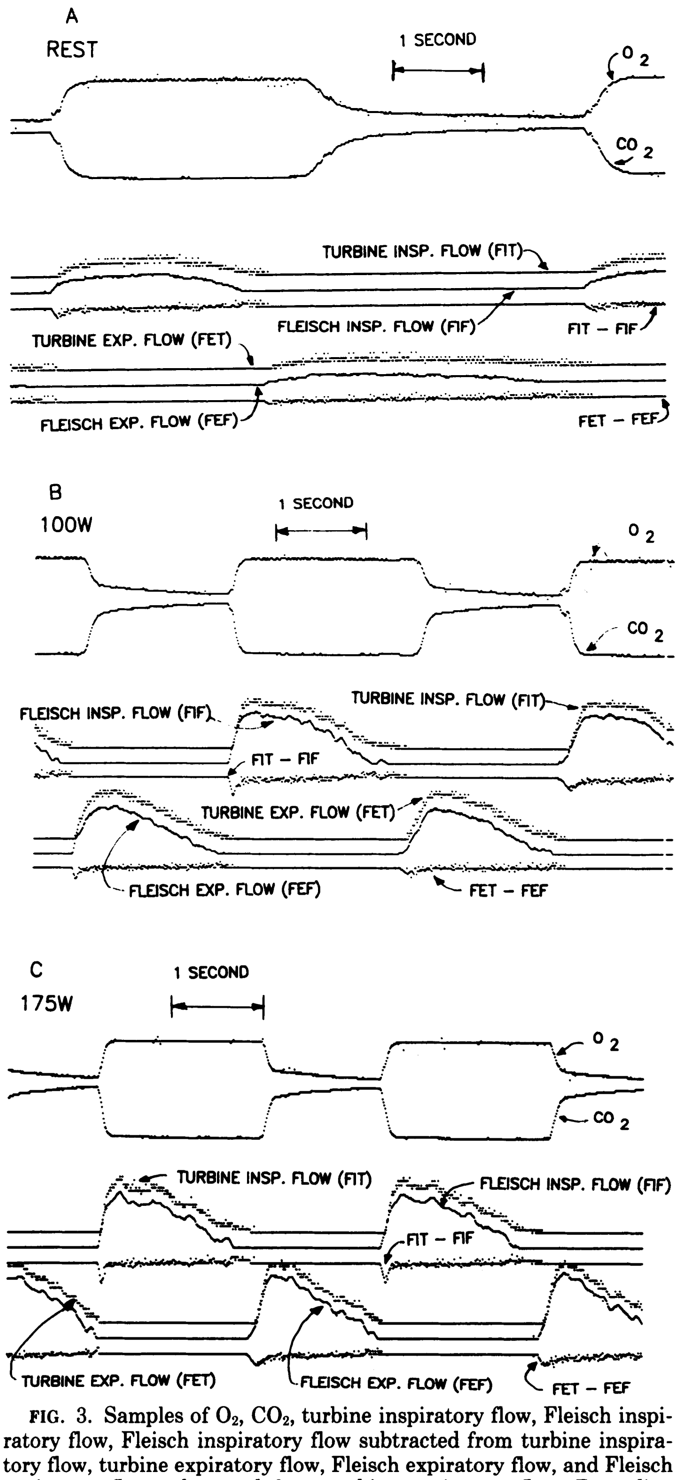

FIG. 3. Samples of O_2, CO_2, turbine inspiratory flow, Fleisch inspiratory flow, Fleisch inspiratory flow subtracted from turbine inspiratory flow, turbine expiratory flow, Fleisch expiratory flow, and Fleisch expiratory flow subtracted from turbine expiratory flow. Recording period is 7.2 s. Both O_2 and CO_2 signals were shifted left by 0.300 s to compensate for gas transport delay. All flow signals were converted to same units (l/min) to facilitate visual comparison. *A*: at rest; *B*: during 100-W exercise; *C*: during 175-W exercise.

sured using a Tissot spirometer. $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ from the Douglas bag method were calculated and compared with the test results reported by the computerized breath-by-breath exercise test system using either the turbine flowmeter or the Fleisch pneumotachometer. For the flush of expired gas from the balloon, both O_2 and CO_2 delay times were calculated for the turbine flowmeter and the Fleisch pneumotachometer. Delay time was calculated using two different algorithms: *1*) the center of the rising CO_2 curve or the center of the falling O_2 curve (1, 6), and *2*) 60% of the rising CO_2 curve or 60% of the falling O_2 curve.

TABLE 1. *System validation with Fleisch pneumotachometer and mass spectrometer compared with Douglas bag method*

Work Load	Test No.		Computer Method (C)	Douglas Bag Method (DB)	Comparison (C-DB)/DB, %
		A. Sampling from two-way valve			
Rest	*30*	$\dot{V}_E$	8.56	8.30	3.11
		$\dot{V}O_2$	0.36	0.34	4.74
		$\dot{V}CO_2$	0.32	0.31	3.70
		R	0.89	0.90	−0.99
	31	$\dot{V}_E$	7.93	7.83	1.37
		$\dot{V}O_2$	0.33	0.32	1.92
		$\dot{V}CO_2$	0.30	0.30	0.69
		R	0.90	0.91	−1.21
100 W	*32*	$\dot{V}_E$	34.65	34.56	0.26
		$\dot{V}O_2$	1.54	1.50	2.97
		$\dot{V}CO_2$	1.69	1.66	1.51
		R	1.10	1.11	−1.41
	33	$\dot{V}_E$	35.30	34.90	1.16
		$\dot{V}O_2$	1.63	1.58	3.46
		$\dot{V}CO_2$	1.63	1.61	1.51
		R	1.00	1.02	−1.89
175 W	*40*	$\dot{V}_E$	35.16	34.30	2.52
		$\dot{V}O_2$	1.55	1.50	3.14
		$\dot{V}CO_2$	1.71	1.68	1.97
		R	1.11	1.12	−1.13
	41	$\dot{V}_E$	38.24	37.08	3.14
		$\dot{V}O_2$	1.78	1.71	4.05
		$\dot{V}CO_2$	1.71	1.67	2.44
		R	0.96	0.98	−1.55
		B. Sampling from saliva trap			
Rest	*34*	$\dot{V}_E$	8.11	7.97	1.80
		$\dot{V}O_2$	0.32	0.31	3.60
		$\dot{V}CO_2$	0.27	0.26	0.98
		R	0.83	0.86	−2.53

Values for expiratory flow ($\dot{V}_E$), O_2 uptake ($\dot{V}O_2$), and CO_2 output ($\dot{V}CO_2$) are in l/min; values for resistance are for $\dot{V}CO_2/\dot{V}O_2$.

RESULTS

Samples of flow signals at rest, during 100-W exercise, and during 175-W exercise are shown in Fig. 3. To facilitate the visual comparison, both the Fleisch and turbine flow signals were scaled to identical units (l/min) using flowmeter characteristics obtained from the calibration procedure. Both the O_2 and CO_2 signals were advanced by 300 ms to compensate for mass spectrometer response time and sampling tubing gas transport delay. Table 1*A* compares the calculated results ($\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$) of the computerized Fleisch pneumotachometer system vs. the Douglas bag method, and Table 2*A* compares the computerized turbine flowmeter system vs. the Douglas bag method.

The $\dot{V}_E$ measurements of the Fleisch pneumotachometer system (see Table 1*A*) were within 3.11% accuracy at rest, 1.16% accuracy during 100-W exercise, and 3.14% accuracy during 175-W exercise. Volume measurements of the turbine flowmeter system (see Table 2*A*) were within 3.10% accuracy at rest, 2.30% accuracy during

TABLE 2. *System validation with turbine flowmeter and mass spectrometer compared with Douglas bag method*

Work Load	Test No.		Computer Method (C)	Douglas Bag Method (DB)	Comparison (C-DB)/DB, %
		A. Sampling from two-way valve			
Rest	*30*	$\dot V_E$	8.56	8.30	3.10
		$\dot V_{O_2}$	0.41	0.34	20.35
		$\dot V_{CO_2}$	0.37	0.31	19.35
		R	0.89	0.90	−0.83
	31	$\dot V_E$	7.83	7.82	0.02
		$\dot V_{O_2}$	0.38	0.32	16.42
		$\dot V_{CO_2}$	0.34	0.29	15.20
		R	0.90	0.91	−1.05
100 W	*32*	$\dot V_E$	35.06	34.57	1.41
		$\dot V_{O_2}$	1.64	1.50	9.59
		$\dot V_{CO_2}$	1.80	1.66	8.09
		R	1.10	1.11	−1.37
	33	$\dot V_E$	35.69	34.89	2.30
		$\dot V_{O_2}$	1.74	1.58	10.56
		$\dot V_{CO_2}$	1.75	1.61	8.53
		R	1.00	1.02	−1.83
175 W	*40*	$\dot V_E$	33.93	34.28	−1.03
		$\dot V_{O_2}$	1.58	1.50	5.27
		$\dot V_{CO_2}$	1.75	1.68	4.11
		R	1.11	1.12	−1.10
	41	$\dot V_E$	36.03	36.96	−2.52
		$\dot V_{O_2}$	1.78	1.71	3.97
		$\dot V_{CO_2}$	1.70	1.67	1.72
		R	0.95	0.98	−2.17
		B. Sampling from saliva trap			
Rest	*34*	$\dot V_E$	8.07	7.77	3.75
		$\dot V_{O_2}$	0.39	0.30	30.32
		$\dot V_{CO_2}$	0.33	0.26	27.73
		R	0.84	0.86	−1.99

See Table 1 for definitions of abbreviations and units of measure.

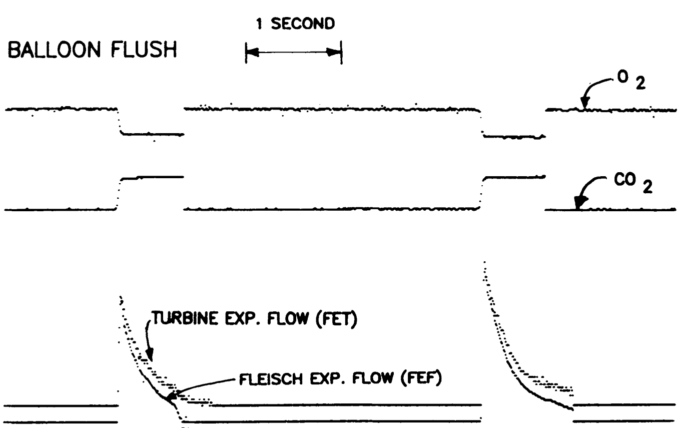

FIG. 4. Balloon flush signals of O_2, CO_2, turbine expiratory flow signal, Fleisch expiratory flow signal, and Fleisch expiratory flow subtracted from turbine expiratory flow. Recording period is 7.2 s. Both O_2 and CO_2 signals were shifted left for 0.300 s and all flow signals were converted to same unit (l/min).

100-W exercise, and 2.52% accuracy during 175-W exercise. The $\dot V_{O_2}$ and $\dot V_{CO_2}$ measurements of the Fleisch pneumotachometer system (see Table 1*A*) were within 4.74% accuracy at rest, 3.46% accuracy during 100-W exercise, and 4.05% accuracy during 175-W exercise. The $\dot V_{O_2}$ and $\dot V_{CO_2}$ measurements of the turbine flowmeter system (see Table 2*A*) had errors as large as 20.35% at rest, 10.56% during 100-W exercise, and 5.27% during 175-W exercise.

A sample of the input signals recorded from the flush of expired gas from the balloon is illustrated in Fig. 4. Both O_2 and CO_2 signals were advanced by 300 ms to compensate for gas delay. During the five delay-time determination trials, for both the 60% and the center of the changing gas concentration curve algorithms, the time for the turbine to sense the fast-flow signal was within 10 ms of the time for the Fleisch to sense the fast flow.

DISCUSSION

From Tables 1*A* and 2*A*, it can be seen that volume measurement for both the Fleisch pneumotachometer and turbine flowmeter were within 4% accuracy, consistent with the report of Davis and Lamarra (3). The accuracy of the Fleisch pneumotachometer-mass spectrometer system, as compared with the standard Douglas bag method, was within 5% for $\dot V_{O_2}$ and $\dot V_{CO_2}$ at rest, 100-W exercise, and 175-W exercise. To our surprise, the errors of the turbine flowmeter-mass spectrometer system were large, in the range of 15–21% for $\dot V_{O_2}$ and $\dot V_{CO_2}$ at rest. However, as the work load increased, the $\dot V_{O_2}$ and $\dot V_{CO_2}$ errors for the turbine system decreased. For example, during 175-W exercise the errors for $\dot V_{O_2}$ and $\dot V_{CO_2}$ measurements were comparable to those of the Fleisch system. The possibility that the errors were caused by inappropriate determination of gas delay time was ruled out with the balloon-filled expired gas study. Repeated tests showed that the determined delay time values were consistent and within 10 ms (one sampling point) between the turbine system and the Fleisch system.

Examination of the derived curve (Fleisch expiratory flow subtracted from the turbine expiratory flow) from the balloon flush study (Fig. 4), however, showed that the turbine flow signal lagged behind the Fleisch flow signal. Visual observations of human breath data (Fig. 3) also revealed that the turbine flow signal always lagged behind the Fleisch signal at the start of inspiration or expiration (the "lag-before-start" effect). The slower the initial inspiratory or expiratory flow, the longer the delay (2). The relationship between the CO_2 curve and the turbine inspiratory flow curve (Fig. 3) confirmed the lag. In Fig. 3, the Fleisch inspiratory flow started to rise when the CO_2 curve (delay time compensated) dropped. But the turbine flow signal stayed at zero for another 40–80 ms (4–8 sampling points) after the CO_2 signal decreased. For a system with dead space, CO_2 concentration should not drop before inspiration starts. These observations support the supposition that the turbine does not appropriately sense the flow signals at the start of inspiration or expiration.

Another major difference between the turbine flowmeter and the Fleisch pneumotachometer occurred at the end of the inspiration or expiration (4). The turbine flow signals did not return to zero like the Fleisch signals (the spin-after-stop effect) (Fig. 3). Instead, the turbine flow signals continued to indicate flow for a few moments. Sometimes the turbine flow continued until the

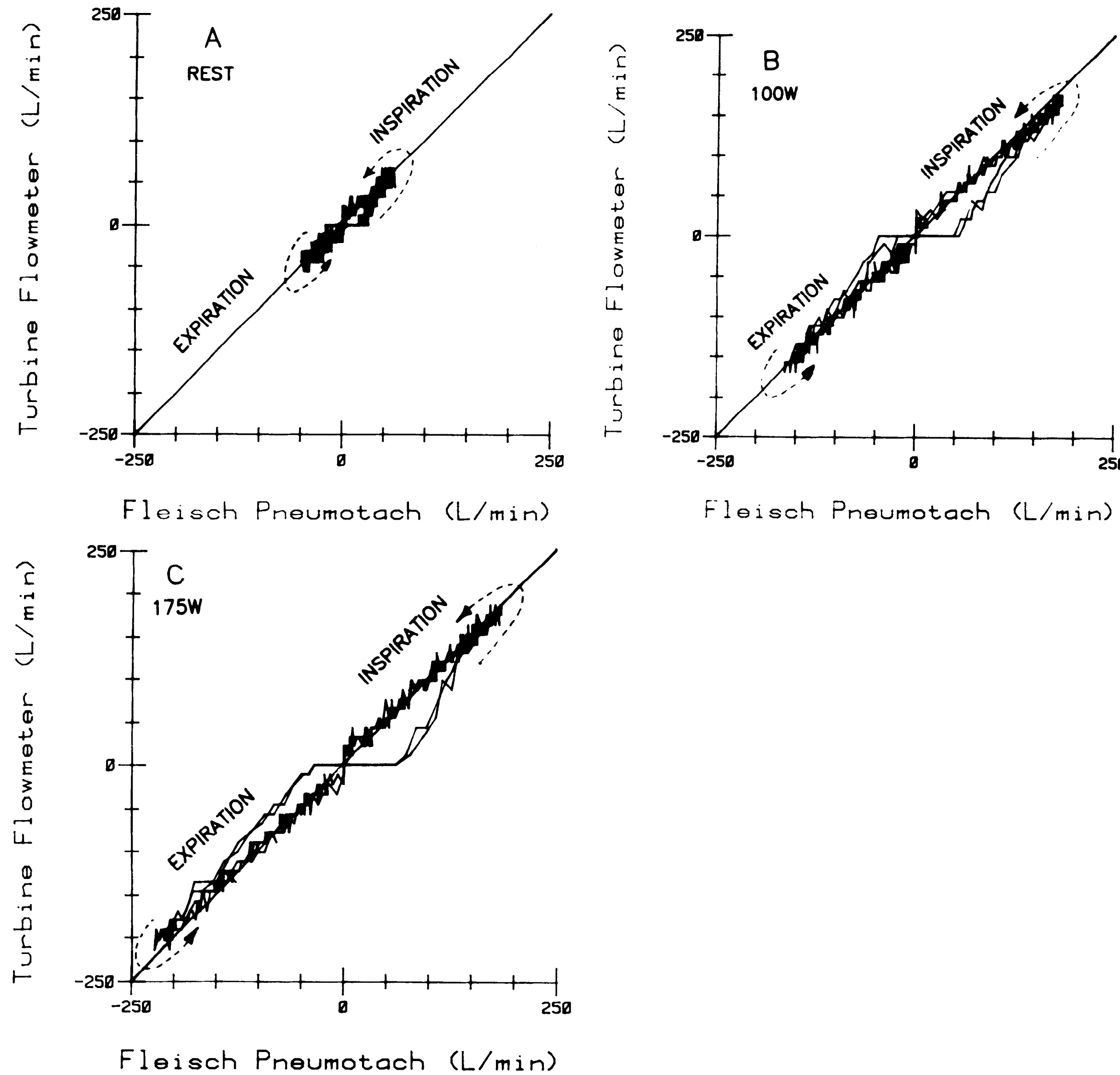

FIG. 5. Turbine vs. Fleisch flow measurement of 2 complete breaths from Fig. 3 are illustrated. Inspiratory flows are plotted at *upper right* (positive values). Expiratory flows are plotted at *lower left* (negative values). Notice "turbine hysteresis" phenomenon for both inspiration and expiration. *A*: at rest. *B*: during 100-W exercise. *C*: during 175-W exercise.

beginning of the next inspiration or expiration. This was especially evident for slow breaths (Fig. 3*A*).

The lag-before-start and spin-after-stop effects of the turbine flowmeter system can be considered an alignment problem of matching the gas concentration signals to flow signals, which is critical for the measurement of $\dot{V}O_2$ and $\dot{V}CO_2$ using a breath-by-breath method. For instance, $\dot{V}CO_2$ is calculated as the amount of CO_2 inflow during inspiration subtracted from the amount of CO_2 outflow during expiration. If the flow measurement lags behind the actual signal at the beginning of the inspiration, the computer will not be able to subtract all the amount of CO_2 coming from the dead space during this time lag, resulting in a larger than actual $\dot{V}CO_2$. During expiratory phase, if the expiratory flow signal continues after the actual airflow terminates, a larger than actual CO_2 outflow will be accumulated, resulting in an erroneously large $\dot{V}CO_2$. The alignment of the gas concentration and flow signals becomes increasingly critical as the "sampling dead space" (the dead space from room air entry to the gas-sampling point) increases. For example, in *test 34* at rest, the mass spectrometer sampled from the saliva trap between the turbine flowmeter and the mouthpiece, instead of at the two-way valve. The sampling dead space now included the turbine flowmeter and the saliva trap, in addition to the dead space inside the two-way valve. The error in $\dot{V}O_2$ increased to 30.32% for the turbine flowmeter-based system (Table 2*B*), compared with only 3.60% for the Fleisch pneumotachometer-based system (Table 1*B*).

The lag-before-start and spin-after-stop effects can be explained by the friction and the inertia of the turbine. At the beginning of a breath when the flow starts, the turbine will not immediately start to spin because of the friction and inertia. As the flow increases, the friction is overcome and the turbine begins to spin. At the end of the breath when the flow stops, the momentum of the turbine keeps the turbine spinning until finally the mo-

TABLE 3. *Effect of reduced delay time and partial cutoff of spin-after-stop to measurement of turbine flowmeter-based system*

Work Load	Test No.		Standard, %	Reduced Delay, %	Partial Cutoff, %	Reduced Time and Partial Cutoff, %
		A. Sampling from two-way valve				
Rest	*30*	$\dot V_E$	3.10	3.13	3.18	3.20
		$\dot V_{O_2}$	20.35	13.81	3.00	−3.59
		$\dot V_{CO_2}$	19.35	12.78	2.12	−4.51
	31	$\dot V_E$	0.02	0.05	0.13	0.15
		$\dot V_{O_2}$	16.42	9.45	−11.06	−17.89
		$\dot V_{CO_2}$	15.20	8.19	−12.04	−18.90
100 W	*32*	$\dot V_E$	1.41	1.37	1.40	1.37
		$\dot V_{O_2}$	9.59	1.78	9.42	1.58
		$\dot V_{CO_2}$	8.09	0.28	7.92	0.09
	33	$\dot V_E$	2.30	2.29	2.30	2.29
		$\dot V_{O_2}$	10.56	1.48	10.45	1.34
		$\dot V_{CO_2}$	8.53	−0.55	8.42	−0.69
		B. Sampling from saliva trap				
Rest	*34*	$\dot V_E$	3.75	3.81	3.93	3.95
		$\dot V_{O_2}$	30.32	19.71	4.67	−5.98
		$\dot V_{CO_2}$	27.73	17.13	2.25	−8.40

Standard, gas delay time at 300 ms; reduced delay, gas delay time reduced to 250 ms; partial cutoff, turbine signal trailing end was not included for calculation after flow signal dropped to 1 digital pulse (~2 ml) per sampling interval (10 ms) for 3 times; reduced delay and partial cutoff, combination of reduced delay and partial cutoff. See Table 1 for definitions of abbreviations and units of measure.

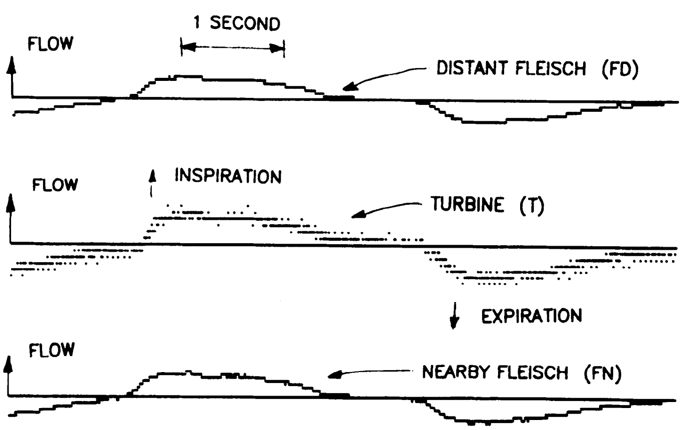

FIG. 6. Flow signals at rest, measured by a distant Fleisch pneumotachometer, a turbine flowmeter, and a nearby pneumotachometer. Distant Fleisch, turbine, and nearby Fleisch were connected in series. Flow signals recorded during 6.4-s measurement. Inspiration flow is plotted as positive and expiration signal is plotted as negative. Maximum inspiration flow (distant Fleisch) is 70 A/D units. Maximum inspiration flow (turbine) is 6 pulses/10 ms. Maximum inspiration flow (nearby Fleisch) is 73 A/D units. "Lag-before-start" and "spin-after-stop" effects did not disappear with elimination of Hans-Rudolph two-way valve.

mentum is decreased to zero by the friction. During exercise at both 100- and 175-W work loads, the lag-before-start effect was not as marked because friction is more quickly overcome due to faster flow. At high flows, the spin-after-stop effect is also reduced because the time between end of expiration and start of inspiration is greatly decreased, causing a rapid change of direction for the turbine propeller. This reduces any continued spin-after-stop.

Fig. 5 shows the turbine-Fleisch hysteresis curve for two inspiratory and expiratory breaths. When inspiration starts, the curve moves to the right before moving up toward maximum inspiratory flow. On decreasing the flow, the turbine-Fleisch curve is not retraced but rather follows another route before returning to zero. This "turbine hysteresis" phenomenon is analogous to the phenomenon observed with magnetic materials known as "magnetic hysteresis."

To assess the effect of the lag-before-start and spin-after-stop on the measurement of $\dot V_E$, $\dot V_{O_2}$, and $\dot V_{CO_2}$, the digitized signals recorded on the hard disk were reprocessed with four different algorithms. *1*) The standard algorithm where gas delay time was 300 ms. All the signals including the spin-after-stop from the turbine flowmeter were processed. *2*) The reduced delay time algorithm where gas delay time was reduced to 250 ms. *3*) The partial cutoff algorithm where the turbine flowmeter signals were not included for calculation as soon as the flow dropped to 0.2 l/s (1 digital pulse/10 ms) for >30 ms in either inspiration or expiration. *4*) The combination of reduced delay time and partial cutoff algorithm (results are shown in Table 3). From *tests 30* and *34* of Table 3, the partial cutoff algorithm makes a major correction for the subject at rest, indicating that spin-after-stop effect contributes to a large portion of the $\dot V_{O_2}$ and $\dot V_{CO_2}$ measurement errors at rest. The disadvantage of this partial cutoff algorithm is that sometimes it may overcompensate, resulting in smaller than actual readings (*test 31* of Table 3). The reduced delay time algorithm decreased the $\dot V_{O_2}$ and $\dot V_{CO_2}$ by 7–10% with the reduction of delay time by 50 ms. However, the lag-before-start effect varies in the time lag, depending on the exercise conditions. Notice that for all the four algorithms, the $\dot V_E$ remained virtually the same.

Because the turbine flowmeter is normally used without the Hans-Rudolph two-way valve, a question was raised about whether the flow resistance or the potential leakage of the valve at low flow rates caused the lag-before-start or spin-after-stop. A distant Fleisch pneumotachometer, a turbine flowmeter, and a nearby Fleisch pneumotachometer were connected in series, without the two-way valve in between. The same human subject breathed through the flowmeter sets at rest. As shown in Fig. 6, the lag-before-start and spin-after-stop effects still existed. Therefore, these effects are not related to the two-way valve used in the former studies.

With the algorithm used in this study, the turbine flowmeter, because of its nonlinear lag-before-start and spin-after-stop, resulted in larger than acceptable error for the measurement of $\dot V_{O_2}$ and $\dot V_{CO_2}$ at low flow rates. A "variable delay time" scheme, which adjusts the gas delay time according to the flow rate, may be able to compensate for the errors. Future studies will be necessary to determine whether an accurate algorithm can be developed for calculating the variable delay time.

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