A comparison of gas exchange indices used to detect the anaerobic threshold

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CAIOZZO, VINCENT J., JAMES A. DAVIS, JEAN F. ELLIS, JEFF L. AZUS, RICHARD VANDAGRIFF, CARLOS A. PRIETTO, AND WILLIAM C. MCMASTER. *A comparison of gas exchange indices used to detect the anaerobic threshold.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 53(5): 1184–1189, 1982.—This study was undertaken to determine which of four commonly used ventilatory or gas exchange indices provides the most accurate and reliable detection of the anaerobic threshold (AT). Sixteen subjects performed two cycle ergometer tests to volitional fatigue. After 4 min of unloaded cycling, the work rate was increased 20 W/min. Ventilatory and gas exchange measurements were made every 30 s throughout each test. During one of the two tests (randomly assigned), venous blood was also sampled every 30 s for subsequent determinations of blood lactate (HLa) concentration. Four ventilatory and gas exchange indices ($\dot{V}\text{E}$, $\dot{V}\text{CO}_2$, R, $\dot{V}\text{E}/\dot{V}\text{O}_2$) were used separately to detect the AT. The AT determined from systematic increases in HLa concentration was used as the criterion measure. AT values (means ± SE) ($\dot{V}\text{O}_2$, l/min) using $\dot{V}\text{E}$, $\dot{V}\text{CO}_2$, R, $\dot{V}\text{E}/\dot{V}\text{O}_2$, and HLa were 1.79 ± 0.11, 1.74 ± 0.11, 1.58 ± 0.06, 1.84 ± 0.11, and 1.85 ± 0.11 l/min, respectively. The highest correlation between a ventilatory or gas exchange AT and AT$_{\text{HLa}}$ (i.e., criterion measure) was found for $\dot{V}\text{E}/\dot{V}\text{O}_2$ ($r = 0.93$, $P < 0.001$). The $\dot{V}\text{E}/\dot{V}\text{O}_2$ also provided the highest test-retest correlation for detection of the AT ($r = 0.93$, $P < 0.001$). Multiple correlational analyses did not significantly enhance detection of the AT. These results favor the use of $\dot{V}\text{E}/\dot{V}\text{O}_2$ for noninvasive detection of the AT because it proved to be the most sensitive and reliable ventilatory or gas exchange index studied.

validity of noninvasive detection of anaerobic threshold; reliability of noninvasive detection of anaerobic threshold; minute ventilation; carbon dioxide output; respiratory exchange ratio; ventilatory equivalents for oxygen and carbon dioxide

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INITIALLY, the anaerobic threshold (AT) was used clinically by Wasserman et al. (13, 16) to assess the exercise tolerance of individuals with cardiorespiratory diseases. However, in recent years, interest in the AT has become much more diversified. To date, some of the other applications of the AT include *1*) its use in characterizing endurance athletes (11); *2*) exercise prescription (3); *3*) studying the effect of drugs on exercise tolerance (5, 17); *4*) using the AT to measure the effects of endurance training (1); *5*) correlating the AT with muscle fiber composition and biochemical properties of skeletal muscle (4, 6, 11, 12); and *6*) predicting endurance performance (4, 12). With respect to endurance performance, the AT has recently (18) been described as a key parameter which, to a large extent, defines the ability to sustain high-intensity exercise.

To facilitate detection of the AT, numerous investigators have used noninvasive ventilatory and/or gas exchange indices. The AT has been identified by nonlinear increases in minute ventilation (2, 5, 6, 9, 11, 14, 17), nonlinear increases in CO_2 output (2, 9, 14, 16), abrupt systematic increases in the respiratory exchange ratio (2, 7, 13, 14, 16), and systematic increases in the ventilatory equivalent for O_2 uptake without concomitant increases in the ventilatory equivalent for CO_2 output (1, 10, 15, 18).

While earlier studies (2, 10, 13, 16) established the feasibility of using noninvasive techniques to detect the AT, it still remains undetermined as to which of the above indices most accurately detects the AT. It has been suggested previously (1) that the AT is easier to detect using the ventilatory equivalent for the O_2 uptake ($\dot{V}\text{E}/\dot{V}\text{O}_2$) compared with either minute ventilation ($\dot{V}\text{E}$) or CO_2 output ($\dot{V}\text{CO}_2$). Also, the feasibility of using the respiratory exchange ratio (R) for detection of the AT has been questioned (2, 16). In addition to the accuracy of detecting the AT, another important consideration is the test-retest reliability of noninvasive AT determinations. While Davis et al. (1) reported a test-retest correlation of 0.94 using $\dot{V}\text{E}/\dot{V}\text{O}_2$ to detect the AT, it is unknown how reliable the other indices might be.

Due to these considerations, there were two primary objectives of this investigation. The first objective was to individually correlate ventilatory and gas exchange AT values (i.e., $\dot{V}\text{E}$, $\dot{V}\text{CO}_2$, R, $\dot{V}\text{E}/\dot{V}\text{O}_2$) with the values determined from blood lactate (HLa) analyses in an effort to find which index yielded the highest correlation with the criterion measure (AT$_{\text{HLa}}$). The second objective was to identify the test-retest correlation of each ventilatory and gas exchange AT. An additional consideration of this study was to examine whether specific combinations of ventilatory and/or gas exchange indices could significantly enhance detection of the AT compared with the use of single indices.

METHODS

Sixteen male ($n = 14$) and female ($n = 2$) subjects between 20 and 31 yr participated in this study. The mean (±SE) age and weight of the subjects were 23.1 ±

0.9 yr and 72.9 ± 3.0 kg, respectively. See Table 1 for individual data. The activity levels of the subjects varied considerably (sedentary to jogging 7 mi/day). Each subject was informed of all risks and stresses associated with this project and gave written consent to participate in this investigation.

Each subject participated in two test sessions. During each test, the subject was seated on a cycle ergometer (Monark model 850, Quinton Instruments, Seattle, WA) and instructed to begin pedaling at 80 rpm. The first 4 min of each test consisted of unloaded cycling after which time the work rate was increased by 20 W/min until the subject reached volitional fatigue.

During both of the test sessions, the subject breathed through a low-resistance Daniels valve (R-PEL, Los Altos, CA). The expiratory side of the breathing valve was connected to a 5-liter mixing chamber. Using the procedures of Wilmore and Costill (19), gas samples were drawn from the mixing chamber and analyzed for the fraction of mixed expired O_2 ($F\bar{E}_{O_2}$) and the fraction of mixed expired CO_2 ($F\bar{E}_{CO_2}$) using a S-3A O_2 analyzer (Applied Electrochemistry, Sunnyvale, CA) and an LB-2 CO_2 analyzer (Beckman, Fullerton, CA), respectively. The inspiratory side of the breathing valve was connected to a Parkinson-Cowan dry gas spirometer (model i/a 9001E, Dynasciences, Blue Bell, PA). To measure the volume of inspired air, the gas meter was fitted with an optical encoder (model R02533-A50-P18, Renco, Santa Barbara, CA) that provided pulses to a digital panel meter (model 6110, Newport Laboratories, Costa Mesa, CA). Using the optical encoder, it was possible to obtain a volume resolution of 0.2 liter. Every 30 s during the test $F\bar{E}_{O_2}$, $F\bar{E}_{CO_2}$, and inspiratory volume were fed into a computer (CBM 2001-16, Commodore Business Machines, Santa Clara, CA), and following these procedures it was possible to obtain printouts every 30 s of $\dot{V}E$, $\dot{V}CO_2$, $\dot{V}O_2$, R, $F\bar{E}_{O_2}$, $F\bar{E}_{CO_2}$, $\dot{V}E/\dot{V}O_2$, and the ventilatory equivalent for CO_2 output ($\dot{V}E/\dot{V}CO_2$). After the completion of a test, each of these variables could also be plotted against time.

During one of the two test sessions (randomly assigned), 1-ml blood samples were drawn repeatedly from a nonheparinized 21-gauge vein infusion set (Miniset, Travenol Laboratories, Deerfield, IL) that had been inserted into an antecubital vein. Blood samples were drawn throughout the test at 30-s intervals, corresponding with ventilatory and gas exchange measurements. The blood samples were analyzed for HLa concentration using an ultraviolet enzymatic technique (826-UV, Sigma Diagnostics, St. Louis, MO).

The single indices used individually to determine the AT values of each subject were $\dot{V}E$, $\dot{V}CO_2$, R, $\dot{V}E/\dot{V}O_2$, and HLa, which was the criterion measure. For each of these indices, the following criteria were employed in selecting the AT: *1*) $AT_{\dot{V}E}$ corresponded to the time at which $\dot{V}E$ began to increase nonlinearly; *2*) $AT_{\dot{V}CO_2}$ corresponded to the time at which $\dot{V}CO_2$ began to increase nonlinearly; *3*) AT_R corresponded to the time at which R demonstrated an abrupt systematic increase; *4*) $AT_{\dot{V}E/\dot{V}O_2}$ corresponded to the time at which $\dot{V}E/\dot{V}O_2$ exhibited a systematic increase without a concomitant increase in $\dot{V}E/\dot{V}CO_2$; and *5*) AT_{HLa} corresponded to the time at which there was a systematic increase in HLa above base-line warm-up values. $F\bar{E}_{O_2}$ was not used in this study to detect the AT because increases in the $F\bar{E}_{O_2}$ are analogous to increases in $\dot{V}E/\dot{V}O_2$ (10). According to the criteria outlined above, an independent investigator, who was not involved in the test sessions and was unfamiliar with the subject population, blindly reviewed the plots of each index mentioned above and made determinations of AT values. All AT values are expressed $\dot{V}O_2$ (l/min). The transformation of AT values from time to $\dot{V}O_2$ (l/min) was performed by computing the linear regression equation for $\dot{V}O_2$ vs. time.

TABLE 1. *Age, weight, sex, and anaerobic thresholds of subjects*

Subj No.	Age, yr	Wt, kg	Sex	AT Values, l/min				
				$\dot{V}E$	$\dot{V}CO_2$	R	$\dot{V}E/\dot{V}O_2$	HLa
1	20	83.4	M	2.54	2.54		2.65	2.54
2	22	61.9	M	2.48	2.48	1.89	1.89	2.13
3	20	67.0	M	2.47	2.10	1.47	2.47	2.60
4	24	84.1	M	1.89	1.98	1.79	1.98	1.79
5	20	62.6	M	1.31	1.20	1.41	1.41	1.31
6	20	76.0	M	1.76	1.56		1.76	1.66
7	20	75.0	M	1.97	1.97	1.87	2.07	1.97
8	27	58.5	F	1.81	1.81	1.48	1.93	2.26
9	21	68.5	M	1.63	1.63	1.63	1.63	1.52
10	26	84.6	M	1.48	1.48	1.48	1.48	1.48
11	26	96.8	M	1.96	1.96	1.84	2.18	2.07
12	29	77.1	M	1.27	1.27	1.37	1.37	1.59
13	20	63.6	M	1.32	1.32	1.42	1.42	1.32
14	31	85.2	M	1.88	1.76		2.26	2.26
15	21	62.1	F	1.50	1.50		1.40	1.50
16	22	60.0	M	1.36	1.36	1.24	1.47	1.58
Mean	23.1	72.9		1.79	1.74		1.84	1.85
				(1.75)	(1.71)	(1.58)	(1.78)	(1.80)
± SE	±0.9	±3.0		±0.11	±0.11		±0.11	±0.11
				(±0.12)	(±0.11)	(±0.06)	(±0.10)	(±0.12)

$\dot{V}E$, minute ventilation; $\dot{V}CO_2$, CO_2 output; R, respiratory exchange ratio; $\dot{V}E/\dot{V}O_2$, ventilatory equivalent for $\dot{V}O_2$; HLa, blood lactate. Values in parentheses are for $n = 12$, i.e., the corresponding values with the R data.

All correlational analyses were done by computer using the Statistical Package for the Social Sciences (8). In all statistical analyses, the 0.05 level of significance was used.

RESULTS

The individual AT values ($\dot{V}O_2$, l/min) for the subjects as determined by using each single index (i.e., $\dot{V}E$, $\dot{V}CO_2$, R, $\dot{V}E/\dot{V}O_2$, and HLa) are reported in Table 1. The mean (±SE) AT values for each of these indices are 1.79 ± 0.11, 1.74 ± 0.11, 1.58[1] ± 0.06, 1.84 ± 0.11, and 1.85 ± 0.11 l/min, respectively. A zero-order correlation matrix for these indices is presented in Table 2. As shown in this table and illustrated in Fig. 1, the highest correlation between any single ventilatory or gas exchange AT and AT_{HLa} (i.e., the criterion measure) was found for $\dot{V}E/\dot{V}O_2$ ($r = 0.93$, $P < 0.001$). AT_R had the lowest correlation with AT_{HLa} ($r = 0.39$, $P > 0.05$). As illustrated in Fig. 2, $\dot{V}E/\dot{V}O_2$ also provided the highest test-retest correlation

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[1] Means ± SE for respiratory exchange values were computed from $n = 12$ not $n = 16$. See DISCUSSION for further explanation and Table 1 for direct comparison with other indices.

for determinations of the AT ($r = 0.93$, $P < 0.001$).

Multiple regression analyses, biased for a small population sample, were performed using AT_{HLa} as the dependent variable and $AT_{\dot{V}E}$, $AT_{\dot{V}CO_2}$, and $AT_{\dot{V}E/\dot{V}O_2}$ as independent variables. As might be predicted from Table 2, the multiple correlation coefficient did not increase significantly when $AT_{\dot{V}E}$ and $AT_{\dot{V}CO_2}$ were combined with $AT_{\dot{V}E/\dot{V}O_2}$. R was not used in multiple correlational analyses because in four of the subjects, R increased steadily throughout the entire test and no abrupt systematic increase could be discerned.

TABLE 2. *Zero-order correlations between single indices used to detect anaerobic threshold*

	$\dot{V}_E$	$\dot{V}CO_2$	R	$\dot{V}_E/\dot{V}O_2$	HLa
n	16	16	12	16	16
$\dot{V}_E$		0.97* ±0.11	0.66† ±0.18	0.88* ±0.20	0.88* ±0.21
$\dot{V}CO_2$			0.78* ±0.15	0.84* ±0.24	0.83* ±0.25
R				0.58† ±0.37	0.39 ±0.22
$\dot{V}_E/\dot{V}O_2$					0.93* ±0.16
HLa					

Values are means ± SEE; SEE given in units $\dot{V}O_2$ (l/min). See Table 1 for abbreviations. * Significant at $P < 0.001$. † Significant at $P < 0.01$.

The mean (±SE) HLa concentration at the onset of metabolic (lactic) acidosis was 1.71 ± 0.11 mmol/l. Using the lactate data, the mean (±SE) relative AT was 50.4 ± 1.9% of maximal $\dot{V}O_2$ ($\dot{V}O_{2\,max}$). The correlation (±SEE) between AT ($\dot{V}O_2$, l/min) and $\dot{V}O_{2\,max}$ (l/min) was 0.75 ± 0.03 l/min. Previous studies (1, 4) have reported similar findings.

With respect to $\dot{V}O_{2\,max}$, the subjects were rather heterogeneous; the range was 2.62 to 4.79 l/min. The mean (±SE) $\dot{V}O_{2\,max}$ values for the two tests were 3.67 ± 0.16 and 3.72 ± 0.17 l/min, respectively. The test-retest correlation (±SEE) for $\dot{V}O_{2\,max}$ was 0.99 ± 0.11 l/min.

DISCUSSION

While previous studies (2, 10, 13, 16) have shown that during exercise the onset of lactic acidosis (i.e., the AT) can be detected using ventilatory and/or gas exchange indices, the purpose of this study was to extend these earlier findings by determining which of four commonly used indices (i.e., $\dot{V}_E$, $\dot{V}CO_2$, R, or $\dot{V}_E/\dot{V}O_2$) provided the most accurate and reliable detection of the AT. Based upon these two criteria (i.e., accuracy and reliability), it was found that $\dot{V}_E/\dot{V}O_2$ was the best single index for detecting the AT. There are several considerations that might account for this finding. First, using the present protocol with work rate durations of 1 min, there were marked qualitative differences between the patterns of response for $\dot{V}_E$, $\dot{V}CO_2$, and $\dot{V}_E/\dot{V}O_2$. During the tests,

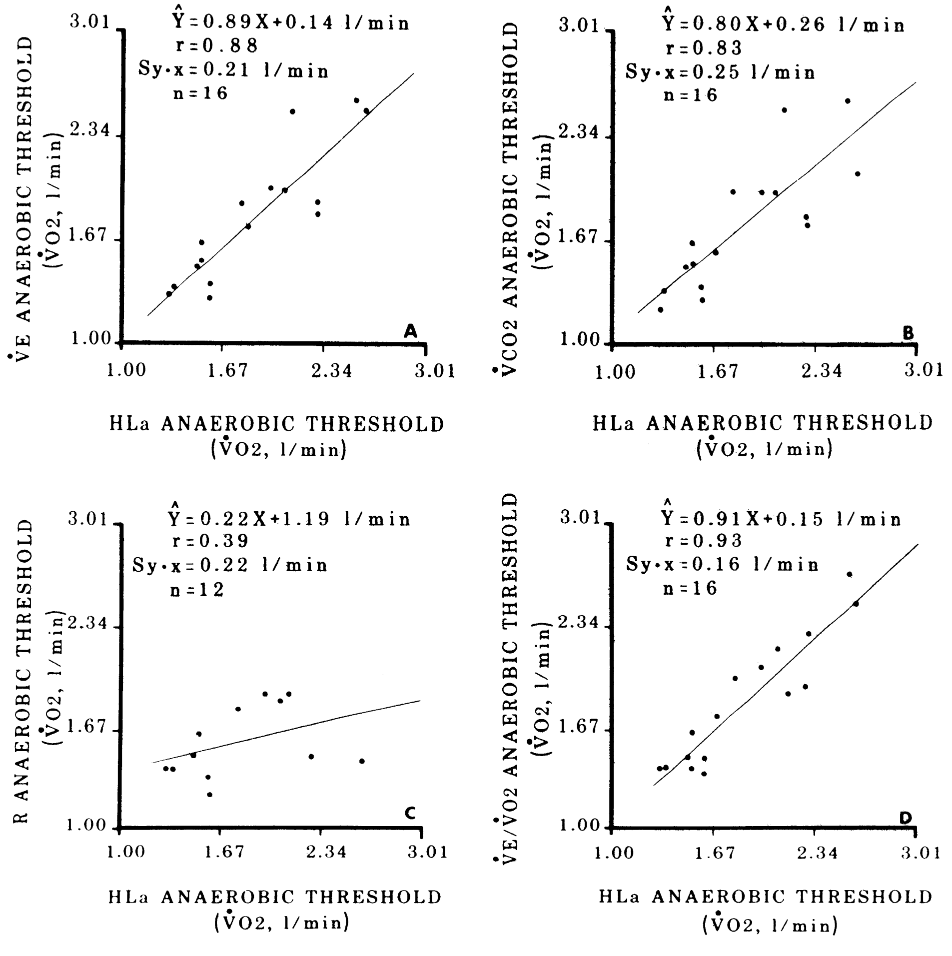

FIG. 1. Illustration of various ventilatory and gas exchange anaerobic threshold values ($AT_{\dot{V}E}$, $AT_{\dot{V}CO_2}$, AT_R, $AT_{\dot{V}E/\dot{V}O_2}$) and their correlation with AT_{HLa} (i.e., the criterion measure of AT).

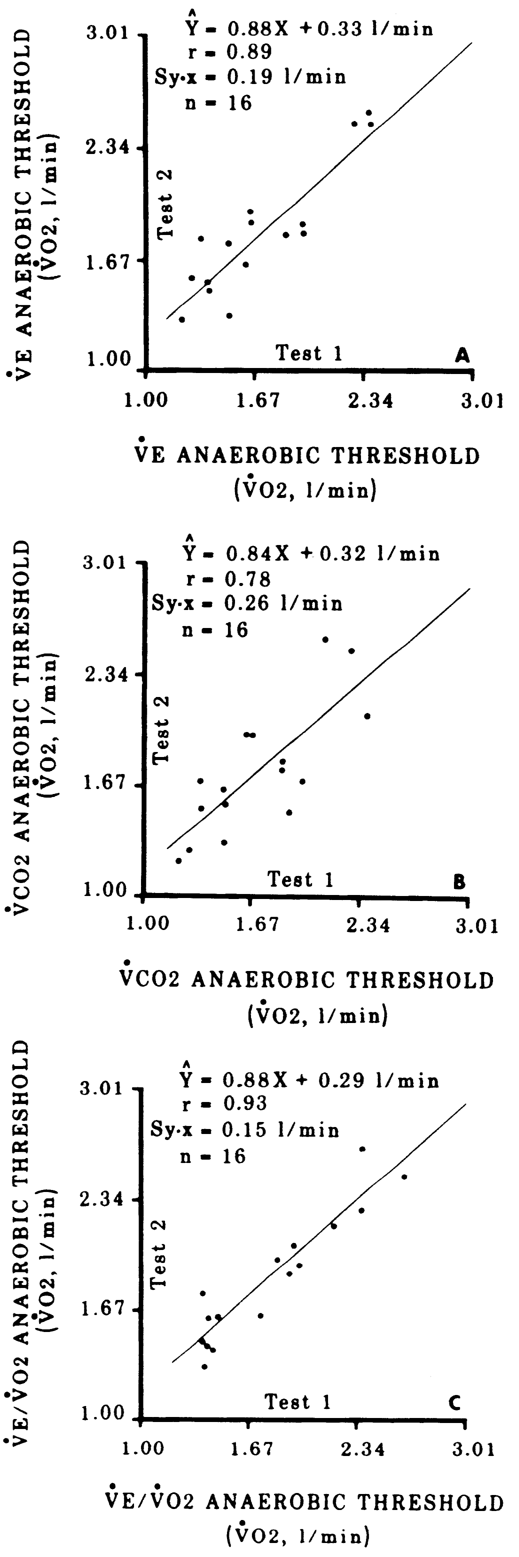

FIG. 2. Test-retest correlation for ventilatory and gas exchange anaerobic threshold determinations. Respiratory exchange ratio is not included because it did not reliably yield detectable AT values based on criteria outlined in METHODS.

$\dot{V}_E/\dot{V}_{O_2}$ would typically fall initially, flatten, and then rise steadily at the AT (Fig. 3). In contrast to this triphasic pattern, $\dot{V}_E$ and $\dot{V}_{CO_2}$ would rise continuously throughout the test, leaving us with less confidence about where the nonlinear break point occurred. A second

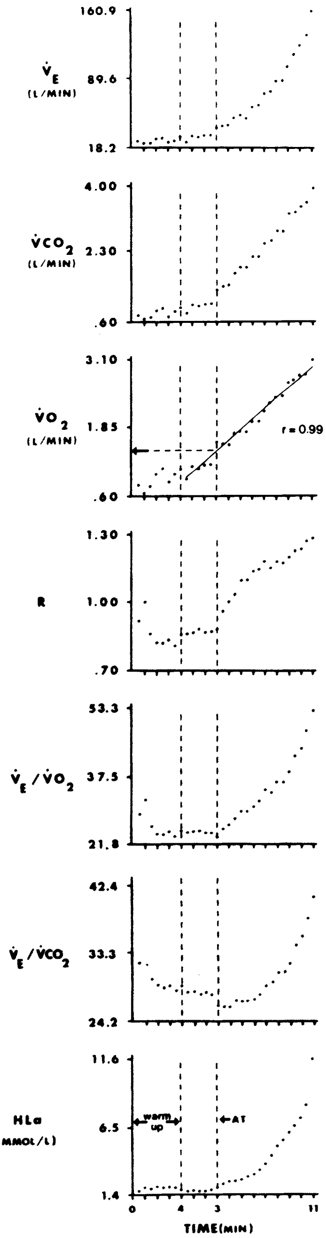

FIG. 3. Ventilatory, gas exchange, and venous blood lactate measurements for *subject 10. First dashed line* indicates onset of incremental work. *Second dashed line* represents AT_{HLa}. Ventilatory equivalent data are calculated and reported as $\dot{V}_E$ BTPS divided by $\dot{V}_{O_2}$ or $\dot{V}_{CO_2}$ STPD. See text for definitions.

consideration is the "dual" criterion that was used in selecting $AT_{\dot{V}_E/\dot{V}_{O_2}}$. As mentioned in METHODS, $AT_{\dot{V}_E/\dot{V}_{O_2}}$ was chosen making sure that there was not a concomitant increase in $\dot{V}_E/\dot{V}_{CO_2}$. It has been reported by Wasserman et al. (15) that this dual criterion provides a more specific determination of the AT, delineating its identification from other causes of nonlinear increases in ventilation such as neurogenic factors or exercise-induced hypoxemia.

With regards to the accuracy of detecting the AT using $\dot{V}_E/\dot{V}_{O_2}$, it is interesting to note that our findings are similar to the observations of Reinhard et al. (10) who found a correlation coefficient of 0.94 when comparing $AT_{\dot{V}_E/\dot{V}_{O_2}}$ with AT_{HLa}. Additionally, the test-retest correlation coefficient ($r = 0.93$) we obtained using $\dot{V}_E/\dot{V}_{O_2}$ to detect the AT is consistent with the findings of Davis et al. (1) who reported a test-retest correlation coefficient of 0.94 for $\text{AT}_{\dot{V}E/\dot{V}O_2}$.

While the difference between the mean AT_{HLa} and mean $\text{AT}_{\dot{V}E/\dot{V}O_2}$ was only 0.01 l/min for the subjects as a group (see Table 1), the mean (±SE) individual error, disregarding the sign of the error, was 0.13 ± 0.02 l/min, which corresponds to a mean (±SE) relative error of 7.4 ± 1.0%. On the average, the determination of $\text{AT}_{\dot{V}E/\dot{V}O_2}$ was one sample interval (i.e., 30 s) different from AT_{HLa}. We suspect that this error might be reduced by using shorter collection intervals (e.g., 15 s) or continuous breath-by-breath measurement techniques.

Contrasting the earlier data of Davis et al. (2) with data reported by Reinhard et al. (10), it might have been expected that the AT would be detected more accurately using $\dot{V}E/\dot{V}O_2$ rather than by using $\dot{V}E$. However, in light of the fact that Davis et al. (2) expressed their AT data as a percent of $\dot{V}O_{2\,\text{max}}$ (%$\dot{V}O_{2\,\text{max}}$) and Reinhard et al. (10) chose to express their AT as $\dot{V}O_2$ l/min, it is difficult to know how comparable the results of these two investigations might be. Findings reported in a more recent study by Davis et al. (1) indicate that expressing AT as $\dot{V}O_2$ l/min favors higher correlations (0.94 vs. 0.91) compared with expressing AT as %$\dot{V}O_{2\,\text{max}}$. Our data support this observation and also indicate that such transformations can have a much greater effect on correlation coefficients. For instance, as shown in Table 2 and Fig. 1*A*, the correlation between $\text{AT}_{\dot{V}E}$ and AT_{HLa} was 0.88 when the data were expressed as $\dot{V}O_2$ l/min. However, when the AT data were transformed to %$\dot{V}O_{2\,\text{max}}$, the correlation between these same indices dropped to 0.69. It appears then that the transformation of AT values to %$\dot{V}O_{2\,\text{max}}$ increases (to varying degrees) the homogeneity of the data and thereby produces lower correlation coefficients. Observations similar to this have been made in the study of body composition.

In some of the early studies (7, 13), the AT was determined by using abrupt increases in R above baseline values. More recently though, Wasserman et al. (16) and Davis et al. (2) reported that of the various ventilatory and gas exchange indices used to detect the AT, R was the least sensitive. Our findings are in agreement with these more recent observations, and it should be emphasized that in four of the subjects involved in this study, R rose steadily throughout the entire exercise test and no abrupt systematic increase could be discerned. As pointed out by Wasserman et al. (16) and Davis et al. (2), this may have been due to the elevation of the metabolic respiratory quotient as the work rate was increased. The poor ability to discern the AT using R might explain the disparity between the two previous investigations of Davis et al. (1, 2) that reported markedly different test-retest correlations of the AT. In the earlier investigation (2), AT values were determined by collectively reviewing the plots of $\dot{V}E$, $\dot{V}CO_2$, R, and $F\bar{E}_{O_2}$. By following these procedures, a test-retest correlation of 0.75 was obtained. In the more recent study (1), AT values were chosen, as mentioned above, using $\dot{V}E/\dot{V}O_2$, and a test-retest correlation of 0.94 was found. In view of the fact that we found $\dot{V}E/\dot{V}O_2$ (which is analogous to $F\bar{E}_{O_2}$) to be a good index of the AT and R a poor index of the AT, it is not surprising that a lower test-retest correlation was reported in the earlier study of Davis et al. (2).

From the findings of our study, we have identified five factors that favor using $\dot{V}E/\dot{V}O_2$ to detect the AT: *1*) it has the highest correlation with AT_{HLa}; *2*) it has the highest test-retest correlation; *3*) $\dot{V}E/\dot{V}O_2$ can be easily derived from standard ventilatory and gas exchange measures; *4*) $\dot{V}E/\dot{V}O_2$ exhibits a triphasic pattern that qualitatively allows the investigator to have more confidence in the determination of AT; and *5*) the dual criterion utilizing $\dot{V}E/\dot{V}CO_2$ provides a more specific detection of the AT.

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