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A new method for detecting anaerobic threshold by gas exchange

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BEAVER, WILLIAM L., KARLMAN WASSERMAN, AND BRIAN J. WHIPP. A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol.* 60(6): 2020–2027, 1986.—Excess CO₂ is generated when lactate is increased during exercise because its [H⁺] is buffered primarily by HCO₃⁻ (22 ml for each meq of lactic acid). We developed a method to detect the anaerobic threshold (AT), using computerized regression analysis of the slopes of the CO₂ uptake ($\dot{V}CO_2$) vs. O₂ uptake ($\dot{V}O_2$) plot, which detects the beginning of the excess CO₂ output generated from the buffering of [H⁺], termed the V-slope method. From incremental exercise tests on 10 subjects, the point of excess CO₂ output (AT) predicted closely the lactate and HCO₃⁻ thresholds. The mean gas exchange AT was found to correspond to a small increment of lactate above the mathematically defined lactate threshold [0.50 ± 0.34 (SD) meq/l] and not to differ significantly from the estimated HCO₃⁻ threshold. The mean $\dot{V}O_2$ at AT computed by the V-slope analysis did not differ significantly from the mean value determined by a panel of six experienced reviewers using traditional visual methods, but the AT could be more reliably determined by the V-slope method. The respiratory compensation point, detected separately by examining the minute ventilation vs. $\dot{V}CO_2$ plot, was consistently higher than the AT (2.51 ± 0.42 vs. 1.83 ± 0.30 l/min of $\dot{V}O_2$). This method for determining the AT has significant advantages over others that depend on regular breathing pattern and respiratory chemosensitivity.

lactate threshold; standard bicarbonate; incremental exercise; carbon dioxide output; oxygen uptake

IT HAS BEEN RECOGNIZED since the 1920's by Hill et al. (10) that lactate increases in the blood during heavy exercise. As exercise increases above a certain work rate threshold, an anaerobic component of metabolism causes lactate to increase significantly. This is accompanied by an almost equal reduction in bicarbonate concentration in the blood (4, 23, 29), causing CO₂ production to accelerate, evidenced as an increased respiratory CO₂ output (21, 23, 24). The threshold at which this begins is termed the anaerobic threshold (AT) and has been used as an effective gauge of physical fitness in patients with cardiorespiratory disease (15, 16, 22, 25), as well as in healthy normal subjects, including athletes (6, 12, 13, 18, 19, 30). One way of detecting this metabolic transition is to measure arterial lactate at frequent intervals during a period of increasing work rate and determine where it begins to increase, i.e., a direct lactate threshold (LT)

(3). However, for wide application and to reduce costs a noninvasive method is preferable. This is theoretically possible because bicarbonate is the major buffer of metabolic acids in the body fluids (29), and therefore an increase in blood lactic acid causes an obligatory increase in CO₂ production, which may be detected in the breath.

Traditional methods for AT detection rely on visual inspection of graphical plots of ventilatory equivalents, end-tidal gas concentrations, and respiratory exchange ratio (R) (5–7, 18, 21, 24). Recently, Smith and O'Donnell (19) have used a computer method for detecting the AT from these quantities, by smoothing the data with a cumulative sum technique, followed by threshold detection. Orr et al. (17) have also introduced a computer-implemented method, in which the minute ventilation ($\dot{V}E$) vs. O₂ uptake ($\dot{V}O_2$) curve is analyzed by a three-segment regression analysis to locate an intersection point that is identified as the AT. However, such methods are sometimes inaccurate because of their reliance on ventilatory response to the metabolic acidosis which develops above the AT. Ventilatory changes due to causes other than accelerated CO₂ production ($\dot{V}CO_2$) can interfere with the determination of the AT point or even mask it. Also, in some subjects with insensitive ventilatory chemoreceptors (e.g., obstructive lung disease, obesity, or even normal subjects), the expected ventilatory response may not be present.

The purpose of this investigation was to study the changes in respiratory gas exchange during an incremental exercise test in order to derive an objective mathematical method, based on buffering of lactic acid, which could reliably locate the AT and that is independent of the sensitivity of ventilatory control mechanisms.

MATERIALS AND METHODS

Subjects. Ten healthy male volunteers, ranging in age from 19 to 39 yr, were studied. After 4 min of unloaded exercise, each subject performed an incremental exercise test to the limit of tolerance on a cycle ergometer (Lanoo), with work rate increased in increments of 15 W/min.

Gas exchange measurements. The subjects breathed through a mouthpiece connected to a turbine flowmeter for continuous measurement of inspired and expired volume (Alpha Technologies) and by a mass spectrometry

ter (Perkin-Elmer MGA 1100) for continuous measurement of O_2 , CO_2 , and N_2 partial pressures. $\dot{V}E$ and alveolar $\dot{V}O_2$ and $\dot{V}CO_2$ were computed, breath by breath, using a Hewlett-Packard computer (model 1000) as previously described (1, 2).

Arterial blood analyses. Blood from an indwelling brachial artery catheter (modified Seldinger technique) was sampled at rest, in the unloaded cycling period, and every 2 min during the phase of incremental exercise. These samples were analyzed for lactate and bicarbonate. The pattern of change as related to $\dot{V}O_2$ was previously reported (3, 4).

Gas exchange analysis of AT by V-slope method and independent experts. The method that was selected to detect the AT involves the analysis of the behavior of $\dot{V}CO_2$ as a function of $\dot{V}O_2$ during progressive exercise tests when exceeding the LT is accompanied by the buffering of lactic acid by $[HCO_3^-]$ with a consequent increase in $\dot{V}CO_2$. This results in a transition in the relationship between the $\dot{V}CO_2$ and $\dot{V}O_2$, which is the underlying element in all methods of anaerobic threshold detection by gas exchange. $\dot{V}O_2$ is used as the independent variable because it is the direct index of metabolism. We have termed this AT detection procedure the V-slope method, since it is based on analyzing the slopes of gas (O_2 and CO_2) volume curves.

The gas exchange data were analyzed using an Apple II+ computer, to give estimates of the AT by the V-slope method for each subject.

For comparison with previous work, the gas exchange data were also analyzed by a panel of six experienced reviewers using a visual identification technique that is standard in this laboratory (21). In this method, plots of $\dot{V}E/\dot{V}CO_2$, $\dot{V}E/\dot{V}O_2$, end-tidal PCO_2 (P_{ETCO_2}), end-tidal PO_2 (P_{ETO_2}), and R vs. time are examined, and the AT point is located visually using the following criteria for the transition. 1) The $\dot{V}E/\dot{V}O_2$ curve, having been flat or decreasing, begins to rise as the $\dot{V}E/\dot{V}CO_2$ curve remains constant or decreases. 2) The P_{ETCO_2} -work rate curve is slowly rising or constant, but the P_{ETO_2} -work rate curve, having been declining or flat, begins to rise. 3) The R-work rate curve having been flat or rising slowly, changes to a more positive slope.

These criteria were used jointly to judge the location of the AT, which was compared with that determined by the V-slope analysis. Each panel member independently evaluated the studies of the 10 subjects without prior knowledge of any other results or the identity of any subject. There were thus a potential of 60 independent trials of AT detection. However, the number of recorded observations was only 50 because the above criteria could not be satisfied in all studies. Furthermore, all six panelists could only grade five of the ten subjects.

The changes in lactate and HCO_3^- at the AT estimated by the gas exchange methods were derived from previously reported results in the same studies (3, 4). Tests for significant differences were carried out using paired *t* tests (Ref. 20, p. 83).

RESULTS

$\dot{V}CO_2$ - $\dot{V}O_2$ relationship. Fig. 1 shows the time course of $\dot{V}O_2$ and $\dot{V}CO_2$ during an exercise study with a 5-min

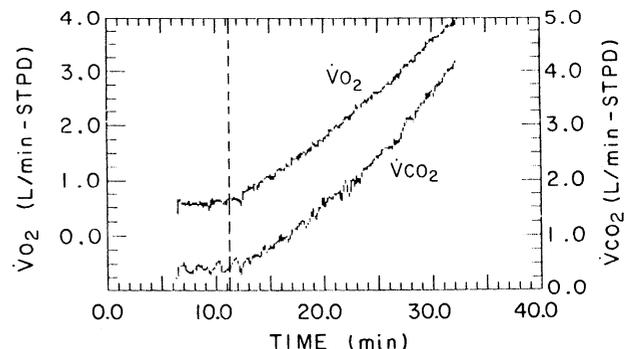


FIG. 1. CO_2 production ($\dot{V}CO_2$) and O_2 uptake ($\dot{V}O_2$) vs. time for a 1-min 15-W incremental exercise study in subject 3. $\dot{V}CO_2$ and $\dot{V}O_2$ are derived from breath-by-breath data smoothed with a 0.15-min moving average filter. Initially, subject performed unloaded cycling. Start of incremental work rate phase is indicated by vertical line.

period of unloaded pedaling followed by 1-min increments in work rate. Since both $\dot{V}O_2$ and $\dot{V}CO_2$ fluctuate breath to breath, due to irregularities in ventilation, these data have been processed by a 9-s moving average filter. This filtering does not obscure the desired information because the underlying relationship between $\dot{V}CO_2$ and $\dot{V}O_2$ is metabolic in origin and not sensitive to ventilatory changes and varies at a rate that is much slower than breath-to-breath variations. In fact, it can be seen in Fig. 1 that a 1-min stair-step increase in work rate does not cause a similar variation of either $\dot{V}O_2$ or $\dot{V}CO_2$. This indicates that when the duration of each work rate is short enough, the damping effect of the physiological mechanisms involved in metabolism, gas storage, and gas transport causes the CO_2 and O_2 delivered to the lung to change smoothly.

After an initial adjustment of the CO_2 stores at the start of the incremental work phase, CO_2 delivered to the lungs rises approximately linearly with O_2 uptake up to the AT. Above the AT, CO_2 output increases more steeply relative to O_2 uptake, as is shown in Fig. 2A which is a plot of $\dot{V}CO_2$ vs. $\dot{V}O_2$ for the study shown in Fig. 1. The two dashed regression lines in Fig. 2A represent the two linear portions of the curve that join at the point where $\dot{V}CO_2$ clearly begins to increase more rapidly.

Figure 2B is a plot of $\dot{V}E$ vs. $\dot{V}CO_2$ for the same study, showing a break point marked by the intersection of the dashed regression lines that represent the two linear segments above and below this point. This point of increased slope marks the start of respiratory compensation (RC) for metabolic acidosis, below which $\dot{V}E$ is closely coupled to $\dot{V}CO_2$ but above which $\dot{V}E$ rises more rapidly in a phase of relative hyperventilation. In this phase, the behavior of $\dot{V}CO_2$ no longer solely reflects metabolic and buffering events in the tissues. In Fig. 2A, the $\dot{V}CO_2$ vs. $\dot{V}O_2$ curve is seen to be approximately linear between the AT and RC points. The AT is located by defining the intersection between this segment and the linear segment of the curve at the lower work rates.

Figure 2C shows $\dot{V}E$ plotted against $\dot{V}O_2$ for the study illustrated in Fig. 1. It has been proposed (17) that a three-segment linear regression model be fitted to the $\dot{V}E$ - $\dot{V}O_2$ relationship to estimate the location of the AT. The RC point shown by the downward arrow is seen to

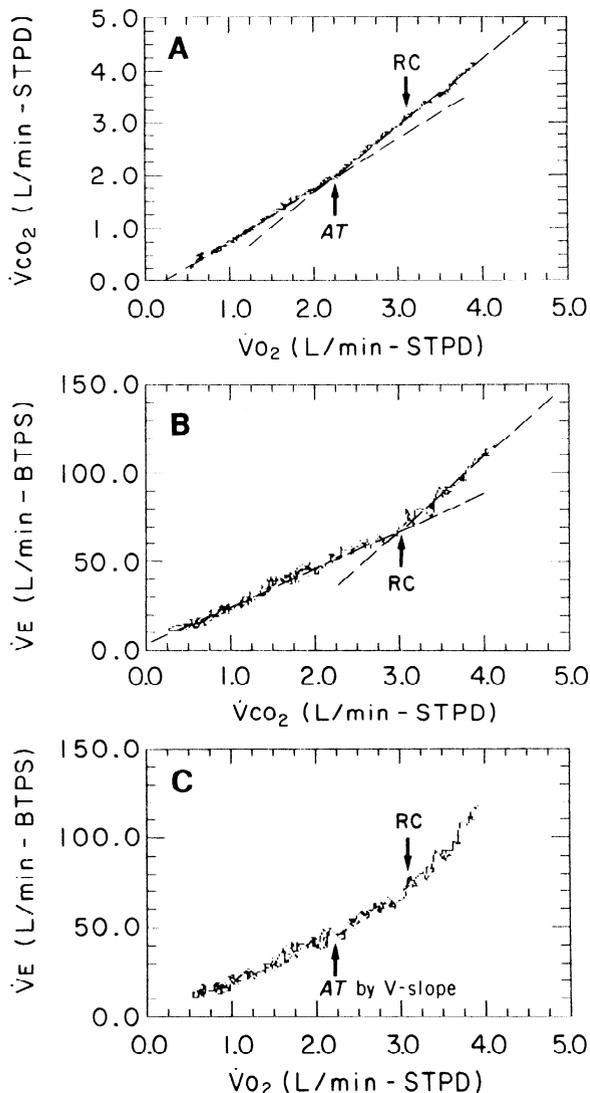


FIG. 2. A: $\dot{V}CO_2$ vs. $\dot{V}O_2$ from Fig. 1 (subj 3), showing regression lines for detecting inflection point (AT point). B: minute ventilation ($\dot{V}E$) vs. $\dot{V}CO_2$ for subject 3, showing regression lines for detecting inflection point (RC point). C: $\dot{V}E$ vs. $\dot{V}O_2$ for subject 3, showing AT and RC points derived separately by analyzing Fig. 2, A and B.

mark the most evident angle in the curve and would be easily detected. The AT (upward arrow) is difficult to detect visually and to define mathematically because the change in slope is small compared with the scatter of the data points. Also a change in slope of $\dot{V}E$ vs. $\dot{V}O_2$ at the point of increased CO_2 output depends on the dynamic sensitivity of the ventilatory control mechanism, which may be quite variable.

Calculation methods. The V-slope method will be described as applied to studies on the cycle ergometer. The subject is first observed during unloaded pedaling, after which the work rate is increased by a constant amount each minute, or at a continuous rate, to a level well above the AT, usually to the level of the subject's maximal effort, so that the maximum O_2 uptake can be measured. The analysis requires that $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, heart rate, and PET_{CO_2} be measured breath by breath.

Data conditioning. The breath-by-breath data points

are transformed by interpolation into data points at regular time intervals so that the analysis is not biased by irregular distribution. A moving average filter is used to smooth the breath-by-breath fluctuations with a width that depends on the amount of noise in the data. (A width of 9 s was used throughout the studies reported here.) It is best to use as little filtering as possible to avoid distortion of the underlying curve shape by the filtering process.

One type of interfering irregularity in the $\dot{V}CO_2$ vs. $\dot{V}O_2$ curve is caused by fluctuations in $\dot{V}CO_2$ that have a recognizable physiological origin and may be corrected. Examples of this can be seen in Fig. 1 where fluctuations occur in the $\dot{V}CO_2$ curve that do not have counterparts in the $\dot{V}O_2$. Such fluctuations can occur anywhere in the study and can significantly affect the precision of AT detection, even with additional digital filtering. These variations are largely correlated with fluctuations in PET_{CO_2} and appear to be associated with irregular oscillations in $\dot{V}E$. The resulting variation in arterial CO_2 partial pressure (Pa_{CO_2}) causes variation in the transport of CO_2 away from the lungs by the pulmonary venous blood, which may be represented as follows

$$\delta\dot{V}CO_2 = [\beta] \cdot \dot{Q} \cdot \delta Pa_{CO_2} \quad (1)$$

where $\delta\dot{V}CO_2$ is the change in CO_2 transport away from the lungs by pulmonary blood, $[\beta]$ is the solubility of CO_2 in blood, \dot{Q} is the cardiac output, and δPa_{CO_2} is the variation of Pa_{CO_2} , approximated by δPET_{CO_2} .

Note that in the latter relationship we do not propose that Pa_{CO_2} and PET_{CO_2} are equal during exercise, they are not (23, 28). Rather, a ventilatory-induced change in Pa_{CO_2} will be closely approximated by a change in PET_{CO_2} . We assume that these CO_2 fluctuations do not show up in the mixed venous flow but, rather, are damped by the capacitive effect of the body stores. Therefore, the change in CO_2 transport away from the lungs (Eq. 1) can be added to the measured respiratory $\dot{V}CO_2$ to give a better approximation to CO_2 transport from the tissues to the lungs, and a smoother $\dot{V}CO_2$ curve.

Figure 3 shows a plot of PET_{CO_2} over the time period from the start of the incremental exercise phase to the end of exercise. The smooth curve is derived by the least-squares fitting of the PET_{CO_2} data points with a third-

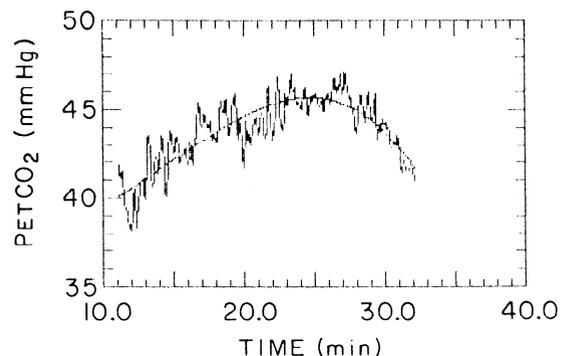


FIG. 3. End-tidal PCO_2 (PET_{CO_2}) from study of subject 3 for time interval from start of incremental phase to end of exercise. Smooth curve is third-order fitting function of PET_{CO_2} curve (see text). Difference between curves is PET_{CO_2} to be used to correct $\dot{V}CO_2$ (Eq. 1 in text).

order function of time (9). The difference between the $\dot{V}E_{CO_2}$ values and the third-order curve describes the short-term fluctuations that will provide the compensation term given in Eq. 1. The most significant corrections extend over periods of 1 min to several.

Stroke volume is assumed to change little after exercise has started, and therefore \dot{Q} is assumed to vary during the study in proportion to heart rate. The level of \dot{Q} to use in Eq. 1 is found by varying \dot{Q} over a range of levels and applying the correction at each level until a minimum is found in the remaining fluctuations of $\dot{V}CO_2$. The $\dot{V}CO_2$ with minimum fluctuations is then used for the V-slope analysis. In the 10 studies, the value of \dot{Q} for unloaded exercise that was used in the correction ranged from 4.5 to 8 l/min.

Figure 4 shows a $\dot{V}CO_2$ vs. $\dot{V}O_2$ curve before and after this correction process, demonstrating the effectiveness of the correction. Unlike digital filtering, this smoothing process removes a physiologically derived source of noise without distorting the ability of $\dot{V}CO_2$ to represent events in the tissues.

Respiratory compensation point. The $\dot{V}E$ vs. $\dot{V}CO_2$ data are divided into two linear segments as described below for the AT (see *Regression analysis*). The intersection of the two segments is the RC point if the change in slope between them is greater than a preselected amount (15% of the initial slope). If an RC point is found, its location is transferred to the $\dot{V}CO_2$ vs. $\dot{V}O_2$ curve (e.g., Fig. 2A) and used as the upper boundary of the AT calculation. Certain subjects, notably patients with obstructive lung disease, may not have an RC point.

Distortion at start of incremental phase. At the start of incremental exercise, $\dot{V}CO_2$ rises with a slower time constant than $\dot{V}O_2$ (11, 14, 27) due to the capacitive effect of changing tissue CO_2 stores. This distorts the $\dot{V}CO_2$ vs. $\dot{V}O_2$ curve and produces an initial curved region, that is excluded from the analysis. We have found that omitting the data of the 1st min after the start of incremental exercise to be usually adequate, but any initial segment of the curve above this with a slope <0.6 was also excluded.

Regression analysis. After the initial processing and definition of the range of calculation, the $\dot{V}CO_2$ vs. $\dot{V}O_2$

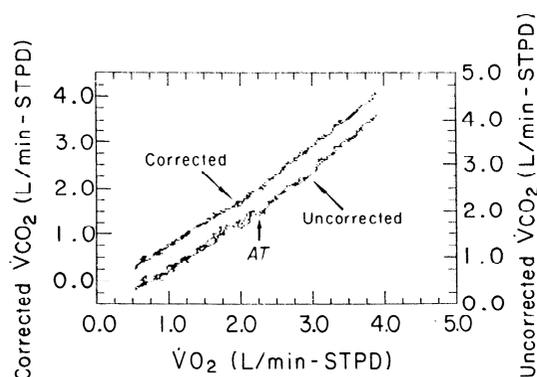


FIG. 4. CO_2 production ($\dot{V}CO_2$) vs. O_2 uptake ($\dot{V}O_2$) for subject 3, showing effect of smoothing $\dot{V}CO_2$ by correcting for changes in gas exchange due to fluctuations in arterial CO_2 partial pressure (P_{aCO_2}) using eq. 1 (see text). Lower curve is uncorrected data plotted in Figs. 1 and 2. Upper curve is corrected for fluctuations in end-tidal PCO_2 (P_{ETCO_2}) as described by Eq. 1 in text.

curve is divided into two regions, each of which is fitted by linear regression (e.g., Fig. 2A). The intersection between the two regression lines is the tentative AT point. The point dividing the two regions is moved systematically until the two lines best fit the data by maximizing the ratio of the greatest distance of the intersection point from the single regression line of the data to the mean square error of regression. This solution is then accepted as an AT if the change in slope from the lower segment to the upper segment is >0.1 . This test eliminates spurious results due to statistical variations in the data. For example, even if no changes in slope exist in the underlying process, the analysis will usually find two segments with a small difference in slope because of noise in the data.

A coefficient of variation of the detected intersection can be estimated by interpreting the data as though the fluctuations are based on a random distribution of the y-axis variable with respect to each regression line. A variance can be calculated of the y-axis location of each regression line (as a function of the x-axis variable) (Ref. 20, p. 149). By geometry, this variance can be translated into a variance of the x-location ($\dot{V}O_2$) of the intersection with the other regression line. Then, assuming that the errors of the regressions are independent, we add the two variances to obtain the total variance of the intersection point on the $\dot{V}O_2$ axis.

Another random error may arise in searching for the optimum intersection point. The division point is moved in intervals that may be of the same order as the uncertainty in locating the intersection. This can be accounted for in the estimate by assuming that a variance due to this source is equal to the variance due to the regression calculation. When these variances are added, a predicted coefficient of variation can be derived (Ref. 20, p. 37) that is an estimate of the uncertainty in the AT detection process. A confidence interval (Ref. 20, p. 56) can also be calculated from this variance.

In Fig. 5, the $\dot{V}CO_2$ vs. $\dot{V}O_2$ curves are plotted for all 10 subjects, showing the regression lines generated by the V-slope analysis to determine the AT points. In some cases the curve has a bend above the RC point, showing the importance of excluding this region from the calculation. The data points appear evenly distributed around the regression lines in the region between the two downward arrows, indicating that the linear model is reasonable.

The estimated 95% confidence intervals for the AT values of the 10 studies ranged from ± 0.05 to ± 0.10 l/min and averaged ± 0.07 l/min or $\pm 3.8\%$ of the $\dot{V}O_2$ at the intersection point. The V-slope values of $\dot{V}O_2$ at the AT are shown in Table 1.

For each subject, the values of $\dot{V}O_2$ at the AT located by the six panel members were averaged together to get the composite value shown in Table 1. The mean $\dot{V}O_2$ at the AT of the V-slope and panel average differ by only 0.02 l/min, not a significant difference ($P > 0.5$). Only 1 panel member detected an AT for all 10 subjects and 2 panelists detected an AT in only 7 of the 10 subjects, but an AT can be detected by all 6 panelists in only 5 out of 10 subjects. The V-slope analysis yielded an AT value

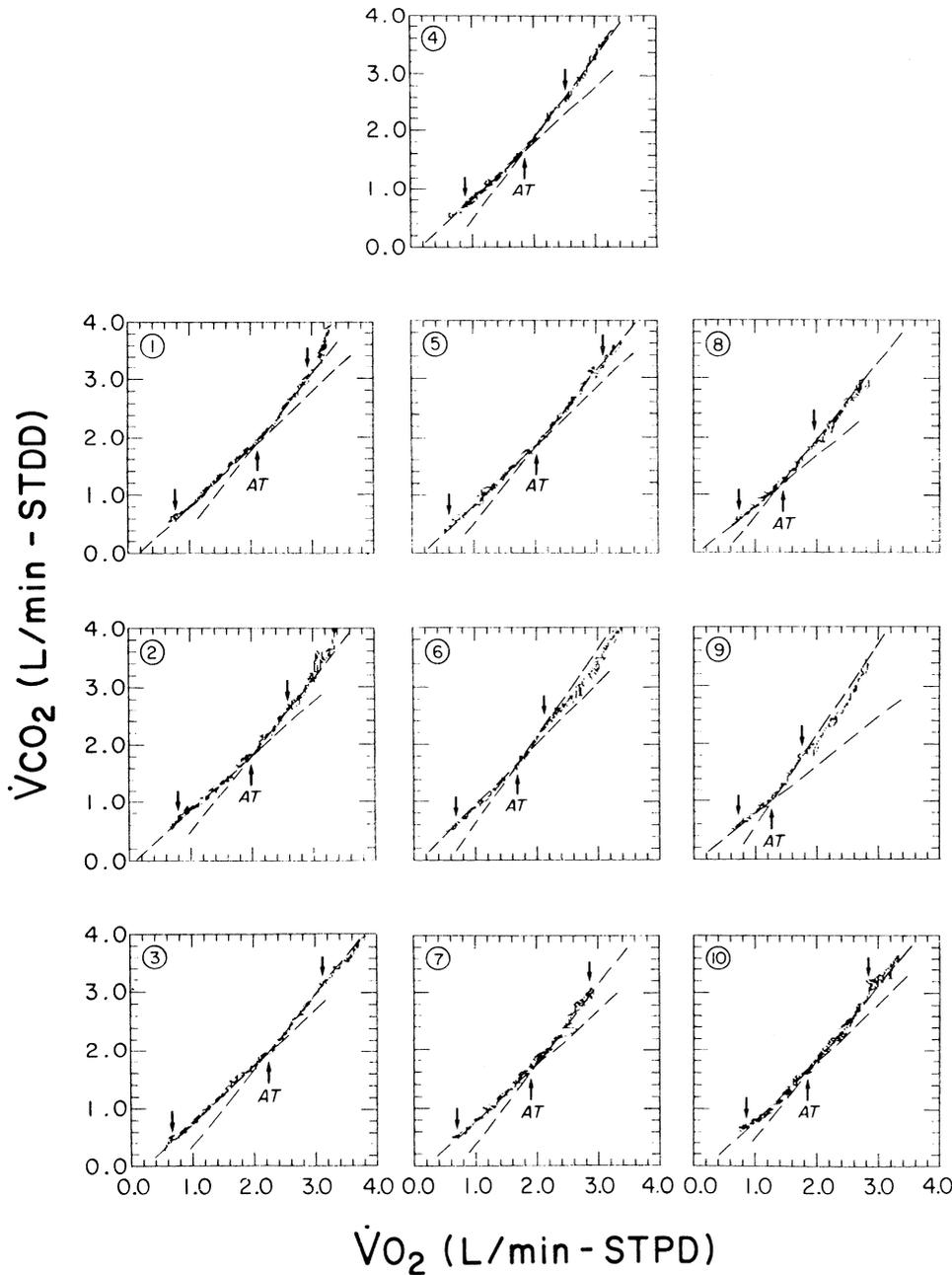


FIG. 5. $\dot{V}\text{CO}_2$ production ($\dot{V}\text{CO}_2$) vs. O_2 uptake ($\dot{V}\text{O}_2$) for 10 subjects of this study, with regression lines established by V-slope calculation to locate anaerobic threshold (AT). In each panel, AT point (intersection between regression lines) is marked by upward arrow. Region used in regression calculation is between downward arrows.

for all 10 subjects (Fig. 5).

The basic reasons for the dispersion of results among the panel members (coefficients of variation, Table 1) can be seen in Fig. 6, A and B, which shows curves of the variables that were analyzed by the panel. The AT points by the panel members are marked by vertical lines. *Subject 9* (Fig. 6A) is the study with best agreement among the panel members, all of whom identified an AT which was quite close to that measured by the V-slope method. *Subject 5* (Fig. 6B), with only two panelists of the six venturing to report an AT, represents the most difficult study to interpret. In this case, the rise in $\dot{V}\text{E}$ lagged the rise in $\dot{V}\text{O}_2$ to such a degree that ventilation-related quantities are not very useful for indicating a transition, whereas the V-slope method is unaffected by the lack of $\dot{V}\text{E}$ response. Visual location of the AT point

depends on the reviewers' interpretation of the time course of the underlying variables in the presence of "noise".

The $\dot{V}\text{O}_2$ at the V-slope AT, the $\dot{V}\text{O}_2$ at the RC point, and the $\dot{V}\text{O}_2$ at maximum work rate ($\dot{V}\text{O}_{2\text{max}}$) are shown in Table 2. The $\dot{V}\text{O}_{2\text{max}}$ was determined from a filtered $\dot{V}\text{O}_2$ vs. time function at the point at which exercise was stopped. The mean $\dot{V}\text{O}_2$ at the RC point is 75% of the mean $\dot{V}\text{O}_{2\text{max}}$, and the mean $\dot{V}\text{O}_2$ at the AT is 73% of mean $\dot{V}\text{O}_2$ at the RC point.

Table 2 also shows the arterial lactate and HCO_3^- concentrations at the V-slope AT points compared with their base-line concentrations (their values at the lactate and HCO_3^- thresholds), which were determined by analyses reported previously (3, 4). The AT was found by the V-slope method to occur at a mean lactate increase of

TABLE 1. Anaerobic thresholds determined by gas exchange methods

Subj No.	V _{O₂} at AT, l/min, Determined by		Coefficients of Variation		No. Detected by Panel
	V slope	Panel avg	V slope	Panel avg	
1	2.08	1.84	0.015	0.237	5
2	1.96	2.14	0.029	0.131	4
3	2.25	2.05	0.016	0.233	6
4	1.84	2.05	0.019	0.089	6
5	2.02	2.31	0.028	0.181	2
6	1.67	1.48	0.020	0.133	5
7	1.92	1.66	0.027	0.017	6
8	1.45	1.71	0.024	0.052	6
9	1.26	1.19	0.019	0.026	6
10	1.86	2.07	0.033	0.175	4
Mean ± SD	1.83±0.30	1.85±0.34	0.023±0.006	0.127±0.080	5

V_{O₂}, O₂ uptake; AT, anaerobic threshold.

0.50 meq/l above the lactate at the LT determined mathematically to be the point just before the lactate begins to rise (3). The mean decrease of HCO₃⁻ below its baseline value is 0.3 meq/l.

The locations of the V-slope gas exchange AT points within the total range of lactate increase and HCO₃⁻ decrease are illustrated in Fig. 7. The curves of Fig. 7 represent, for the 10 studies, the mean lactate variation vs. V_{O₂} (Fig. 7A) from Ref. 3 and the mean standard

bicarbonate variation vs. V_{O₂} (Fig. 7B) from Ref. 4. On these curves are plotted the lactate and HCO₃⁻ values at the gas exchange AT points determined by the V-slope analysis. These points are positioned on the mean curves at the same displacement relative to the thresholds of lactate and HCO₃⁻ as they would have on the curves in their individual studies. Therefore, these plots illustrate the relation of the gas exchange AT values to the arterial lactate and HCO₃⁻ concentrations.

The most significant finding in comparison with the bicarbonate study was that the V_{O₂} at the mean gas exchange AT of 1.83 ± 0.30 l/min (Table 1) is not significantly different from the estimated V_{O₂} at the mean HCO₃⁻ threshold of 1.78 ± 0.24 (SD) l/min (4).

DISCUSSION

It can be seen in Fig. 5 that all V̇CO₂ vs. V̇O₂ curves in this study exhibit an evident change in slope during the incremental phase of exercise. The point where this change occurs signals the arrival of excess CO₂ at the lung and clearly marks a transition in the V̇CO₂-V̇O₂ relationship in the mixed venous blood. This reflects a transition in the CO₂ production rate in the muscles that occurs when lactic acid is produced faster than it is catabolized, and the buffering of H⁺ by HCO₃⁻ results. This observed transition is therefore identified as the gas exchange AT point. For the 10 studies, the mean gas

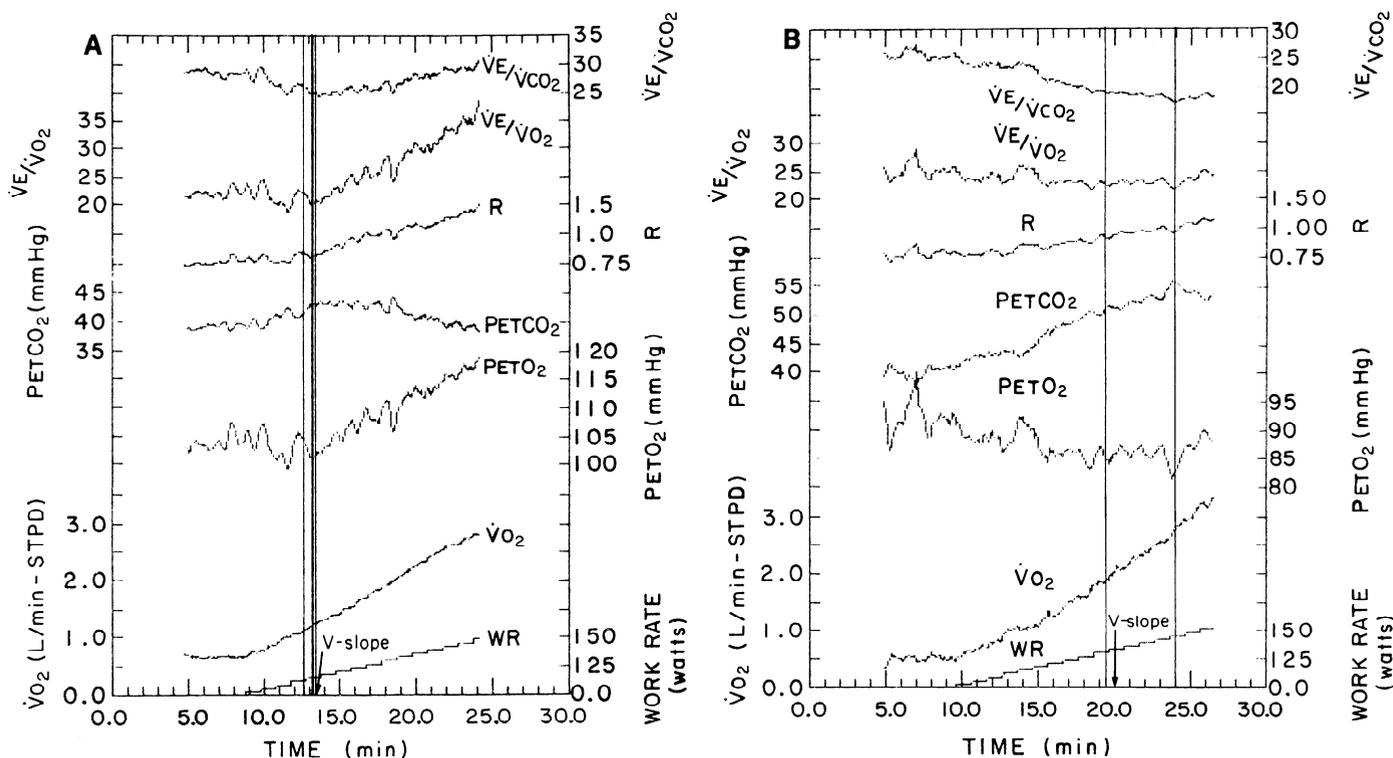


FIG. 6. Quantities used by panel members to detect anaerobic threshold (AT) point, plotted vs. time. AT points detected by panel members are marked by vertical lines. AT point located by V-slope method is indicated by arrow. VE, minute ventilation; VCO₂, CO₂ production; V̇O₂, O₂ uptake; PETCO₂, end-tidal PCO₂; PETO₂, end-tidal PO₂. A: subject 9. All 6 panel members detected anaerobic threshold (AT) points in this study (4 of the AT points were identical). Study represents best agreement among panel members and with V-slope analysis. B: subject 5. Only 2 panel members could detect AT points. Study represents most difficult of 10 studies to interpret by this method. V-slope method showed good agreement with lactate and bicarbonate (HCO₃⁻) thresholds.

TABLE 2. Anaerobic thresholds determined during incremental work rate test

Subj No.	$\dot{V}O_2$, l/min		$\dot{V}O_{2max}$, l/min	[La], meq/l		[HCO ₃ ⁻], meq/l	
	at AT	at RC		at LT	at AT	Base	at AT
1	2.08	2.57	3.10	0.71	1.74	23.8	23.0
2	1.96	2.63	3.36	0.76	0.74	24.6	24.6
3	2.25	3.10	3.95	0.60	1.28	25.0	23.8
4	1.84	2.40	3.20	0.57	1.27	24.2	23.7
5	2.02	2.91	3.40	0.66	1.45	23.7	23.2
6	1.67	2.18	3.50	0.68	1.10	22.4	22.2
7	1.92	2.87	3.60	0.59	1.25	24.6	24.1
8	1.45	2.00	3.00	0.60	0.59	25.9	25.9
9	1.26	1.76	2.90	0.64	0.95	24.0	24.0
10	1.86	2.63	3.45	0.73	1.16	23.2	23.2
Mean ± SD	1.83±0.30	2.51±0.42	3.35±0.31	0.65±0.07	1.15±0.33	24.1±1.0	23.8±1.0

$\dot{V}O_2$, O_2 uptake at anaerobic threshold (AT) and at respiratory compensation point (RC) determined by V-slope analysis; $\dot{V}O_{2max}$, $\dot{V}O_2$ at maximum work rate; [La], lactate concentration at lactate threshold (LT) at V-slope AT; [HCO₃⁻], bicarbonate concentration at base line (Base) at V-slope AT.

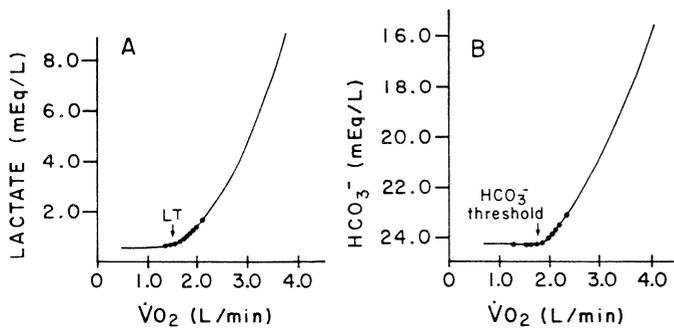


FIG. 7. A: Mean lactate vs. O_2 uptake ($\dot{V}O_2$) curve for the 10 subjects, taken from lactate data of Ref. 3. Plotted points show displacement of gas-exchange anaerobic threshold (AT) detected by V-slope calculation referenced to mean lactate curve. Each point has same location relative to mean lactate threshold (LT) as it was located relative to LT in individual study. Mean lactate value of these points is 0.5 meq/l above lactate level at LT, showing gas exchange AT to be a good estimator of LT. B: Mean bicarbonate (HCO₃⁻) vs. $\dot{V}O_2$ curve for 10 subjects taken from standard HCO₃⁻ data of Ref. 4. Plotted points show displacement of gas exchange anaerobic threshold detected by V-slope calculation referenced to mean HCO₃⁻ curve. Each point has the same location relative to the mean HCO₃⁻ threshold as it was located relative to HCO₃⁻ threshold in individual study. Mean $\dot{V}O_2$ of gas exchange AT does not differ significantly from mean HCO₃⁻ threshold.

exchange AT does not differ significantly from the best estimate of the mean threshold at which arterial HCO₃⁻ begins to decrease [1.83 ± 0.30 (SD) as compared with 1.78 ± 0.24 (SD) l/min of $\dot{V}O_2$, respectively] (4).

The average lactate increment at the gas exchange AT, above the threshold where lactate just begins to rise was $0.5 \text{ meq/l} \pm 0.34$ (SD) (Table 2). This indicates that the gas exchange AT is a good estimate of a LT that is defined as 0.5 meq/l above the prethreshold, or base-line, level. The range of lactate increment at the gas exchange AT in the 10 studies was 0.0–1.0 meq/l. Previous studies (5, 7) have indicated that, in incremental exercise tests, the gas exchange AT is below (7), or no different from (5), the LT. In these and other previous studies, the LT as well as the gas exchange AT were visually identified from graphical data. Because lactate concentration begins to rise slowly at the threshold, selection of the LT is a matter of judgement, particularly when estimated from rectilinear plots. In our lactate studies (3), statis-

tical means were used to identify the LT at the point where arterial lactate just begins to increase. If the LT were defined at a lactate increase of 0.5 meq/l above base line, we also would find no mean difference with the gas exchange AT.

The mean location of the AT detected by the panel was not significantly different from the mean of the V-slope AT points (Table 1). However, the coefficients of variation were quite different (Table 1). These differences may come from two sources: 1) the variables used in the V-slope analysis are less influenced by variations in ventilation unrelated to CO₂ flow; and 2) the V-slope analysis makes use, mathematically, of all relevant data points before and after the AT, whereas visual detection may have difficulty interpreting variations in the graphical data (Fig. 6).

Green et al. (8) found mean lactate at the gas exchange AT to be 2.56 meq/l, which was about 1.5 meq/l above the base-line value. Their multisegment regression analysis (17) attempts to find three linear segments of the $\dot{V}E$ vs. $\dot{V}O_2$ curve connected by two intersection points, the upper of which would correspond to the RC point and the lower to the AT point. Their method will, however, also accept a two-segment solution if a smaller mean square error results (this alternative is needed in case an RC point does not exist). With noisy data and a relatively small change in slope at the AT, this method may find only the RC point and identify it as the AT. The $\dot{V}E$ vs. $\dot{V}O_2$ curve of Fig. 2C illustrates a case where this might happen. If a number of AT values detected in the study of Green et al. (8) were actually RC points, the relatively high mean value of lactate at the AT that they reported could be explained.

The onset of excess CO₂ production in response to lactate accumulation is the fundamental event that is to be detected by gas exchange analysis, and the analysis of $\dot{V}CO_2$ vs. $\dot{V}O_2$ directly addresses this. Although $\dot{V}E$ is, in general, closely coupled to CO₂ flow, there are many conditions when the ventilatory response may lag the metabolic response (e.g., obesity, airflow obstruction, chemoreceptor insensitivity). Methods relying on $\dot{V}E$ changes are not effective in these cases, but the V-slope analysis, which detects the increased CO₂ production

from buffering metabolic acid, addresses the central mechanism of the anaerobic threshold and is therefore more widely applicable.

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