**Viewpoint:** Use aerobic energy expenditure instead of oxygen uptake to quantify exercise intensity and predict endurance performance

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**Abbreviated Title for Running Header**

Use energy not oxygen

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Endurance performance depends on the body’s ability to uptake and utilize oxygen to generate energy (4, 10, 12). As such, scientists often determine exercise intensity and predict endurance performance using the percentage of an individual’s maximum aerobic capacity (often expressed as %\(\dot{\text{V}}\text{O}_2\) max) (4, 10, 12). Scientists calculate %\(\dot{\text{V}}\text{O}_2\) max using measures of an individual’s mode-specific, steady-state submaximal \(\dot{\text{V}}\text{O}_2\) (a measure of exercise economy) and \(\dot{\text{V}}\text{O}_2\) max. However, \(\dot{\text{V}}\text{O}_2\) is only a proxy for the rate of energy that an individual can generate via aerobic metabolism, because it does not account for substrate oxidation, which affects the energy yield per volume of \(\text{O}_2\) uptake (1, 5, 16). The energy yield per volume of \(\text{O}_2\) uptake is \(~7\%\) greater for carbohydrate versus fat oxidation (16). Therefore, accounting for substrate oxidation leads to more accurate calculations of the rate of aerobic energy expended during physical activity and exercise. Accordingly, some recent studies have begun expressing exercise economy as the rate of aerobic energy expenditure (\(\dot{\text{E}}\text{aero}\)) (e.g. watts/kg or kcal/kg/min) rather than \(\dot{\text{V}}\text{O}_2\) (e.g. ml \(\text{O}_2\)/kg/min) (5, 9, 19, 20).

We propose that exercise economy (\(\dot{\text{E}}\text{aero}\)), maximal aerobic capacity (\(\dot{\text{E}}\text{aero \ max}\)), and hence intensity (\(%\dot{\text{E}}\text{aero \ max}\)), should be calculated using units of aerobic energy rather than oxygen. As relative aerobic intensity increases, the ratio of oxidized carbohydrates to fats usually rises until carbohydrates constitute nearly 100% of the oxidized substrates (2, 18). Therefore, \(\dot{\text{E}}\text{aero \ max}\) can be calculated using expired gas analysis and the energy yield of oxidized carbohydrates (21.745 joules/ml \(\text{O}_2\) (16)) when the respiratory exchange ratio (RER) is \(\geq 1.0\), such as at \(\dot{\text{V}}\text{O}_2\) max. Subsequently, \(%\dot{\text{E}}\text{aero \ max}\) can be calculated using submaximal and maximal \(\dot{\text{E}}\text{aero}\).

Compared to relative aerobic intensity expressed as %\(\dot{\text{V}}\text{O}_2\) max, \(%\dot{\text{E}}\text{aero \ max}\) elicits numerically lower relative aerobic intensities when RER is \(< 1.0\) and yields the same relative
aerobic intensities when RER ≥ 1.0 (Fig. 1). Since there is usually a lower ratio of oxidized carbohydrates to fats at relatively easier workloads/slower movement velocities (2, 18), plots of %\( \dot{E}_{\text{aero}} \) max versus workload/velocity have greater slopes than plots of %\( \dot{V}O_2 \) max versus workload/velocity (Fig. 1). Thus, the difference between %\( \dot{E}_{\text{aero}} \) max and %\( \dot{V}O_2 \) max is greater at lower relative aerobic intensities (Fig. 1).

Data from Burke et al. (3) provide a clear example of the differences that can occur between the two methods of calculating relative aerobic intensity. They reported \( \dot{V}O_2 \) and RER for elite race walkers on a high fat/low carbohydrate diet across a series of race-walking stages of increasing intensity (3). Our re-analysis shows that across four submaximal race-walking stages, Burke et al.’s participants exercised at mean relative aerobic intensities that were 2.7 to 4.0 percentage points lower using %\( \dot{E}_{\text{aero}} \) max than using %\( \dot{V}O_2 \) max (one-way ANOVA, p<0.001) (Fig. 1) (3). The difference between %\( \dot{E}_{\text{aero}} \) max and %\( \dot{V}O_2 \) max depended on the race-walking stage (two-way ANOVA interaction effect p=0.004) (Fig. 1) (3), indicating that %\( \dot{E}_{\text{aero}} \) max and %\( \dot{V}O_2 \) max have different slopes when plotted against workload or velocity.

Many exercise studies compare individuals at the same relative aerobic intensities (e.g. 40, 60, 80% \( \dot{V}O_2 \) max) rather than at task specific mechanical power outputs or velocities (2, 5, 11). Yet, equal %\( \dot{V}O_2 \) max increments typically yield unequal %\( \dot{E}_{\text{aero}} \) max increments. Therefore, testing individuals at %\( \dot{E}_{\text{aero}} \) max increments may be more appropriate than %\( \dot{V}O_2 \) max for some scientific questions, such as those related to thermoregulation where heat dissipation in addition to oxygen delivery significantly contribute to the physiological responses during physical activity or exercise (11).

Further, the use of %\( \dot{E}_{\text{aero}} \) max versus %\( \dot{V}O_2 \) max may yield different scientific conclusions when comparing individuals across varied diets (3), aerobic training statuses (2),
exercise durations (6, 11), altitudes (17), and/or ambient temperatures (11). For instance, in the context of endurance performance, the use of %\(\dot{E}_{\text{aero}}\) max is more appropriate than the use of %\(\dot{V}O_2\) max when comparing individuals that differ in aerobic training status. That is because the point at which the ratio of oxidized carbohydrates to fats begins to rapidly increase (crossover point) occurs at a greater %\(\dot{V}O_2\) max in aerobically trained than untrained individuals (2). Hence, the energy yield per volume of O\(_2\) differs between aerobically trained and untrained individuals at the same relative aerobic intensity (%\(\dot{V}O_2\) max and %\(\dot{E}_{\text{aero}}\) max).

The use of \(\dot{E}_{\text{aero}}\) may provide more accurate endurance performance predictions than the use of \(\dot{V}O_2\) alone. To illustrate this, we compared Joyner’s marathon prediction model (12), using \(\dot{V}O_2\) and \(\dot{E}_{\text{aero}}\). Specifically, Joyner (12) predicted a runner’s average marathon running velocity based on their \(\dot{V}O_2\) at lactate threshold (LT) (Equation 1). For the comparison, we updated Joyner’s equation (Equation 1) to incorporate \(\dot{E}_{\text{aero}}\) (Equation 2) using a standard conversion (16) and RER values based on the relationship between RER and %\(\dot{V}O_2\) max from high-caliber runners (Equation 3) (13).

\[
\text{Running velocity (km/hr)} = 0.2878 \times \dot{V}O_2 \text{ (ml O}_2/\text{kg/min)} \text{ at LT} + 1.5867 \quad (\text{Eq. 1})
\]

\[
\text{Running velocity (km/hr)} = 0.7712 \times \dot{E}_{\text{aero}} \text{ (W/kg)} \text{ at LT} + 2.2609 \quad (\text{Eq. 2})
\]

\[
\text{RER} = 0.00005 \times \%\dot{V}O_2 \text{ max}^2 - 0.00301 \times \%\dot{V}O_2 \text{ max} + 0.87729 \quad (\text{Eq. 3})
\]

Joyner slowed his predicted average marathon running velocities by 10% to account for air resistance (7-8%) and an upward drift in \(\dot{V}O_2\) that occurs during prolonged exercise (2-3%) (12). Even though the use of \(\dot{E}_{\text{aero}}\) may eliminate the need to account for \(\dot{V}O_2\) drift, we slowed all predicted average marathon running velocities by 10% for consistency. We used a hypothetical
runner with a 70 ml O₂/kg/min \( \dot{V}O_2 \) max, which equates to a 25.6 W/kg \( \dot{E}_{aero} \) max, and a lactate threshold that occurs at 80% of \( \dot{V}O_2 \) max. Lastly, we predicted the hypothetical runner’s average marathon running velocities using \( \dot{V}O_2 \) (Equation 1) and \( \dot{E}_{aero} \) (Equation 2) at “typical” (0.94) (Equation 3), low (0.80) and high (1.00) RERs (13, 15).

Predicted average marathon running velocities using \( \dot{V}O_2 \) (Equation 1) and \( \dot{E}_{aero} \) (Equation 2) can be identical, or they can differ by 1 to 3% since the energy yield per volume of O₂ varies depending on the metabolic fuel mixture (1, 5, 16). For our hypothetical runner, using \( \dot{V}O_2 \) and \( \dot{E}_{aero} \) at the typical RER yields the same predicted average marathon running velocity, 16.10 km/hr (2:37:18 marathon, hr:min:s). Yet, at low and high RERs, the hypothetical runner’s \( \dot{V}O_2 \)-based predictions remain the same (15.93 km/hr), whereas \( \dot{E}_{aero} \)-based predictions change to 15.65 km/hr (2:41:44 hr:min:s) and 16.28 km/hr (2:35:28 hr:min:s), respectively. Thus, \( \dot{E}_{aero} \)-based endurance performance predictions are likely more accurate than \( \dot{V}O_2 \)-based predictions because they account for the energy yield per volume of O₂.

While the uptake and presence of oxygen is vital for bodily functions (7, 8, 14, 21), aerobic energy expenditure provides a superior measure of exercise economy and maximal aerobic capacity regarding exercise intensity and endurance performance. Accordingly, we encourage our colleagues to report both maximal aerobic capacity (\( \dot{E}_{aero} \) max) and exercise economy (\( \dot{E}_{aero} \)) as rates of aerobic energy expenditure to enable the calculation of relative aerobic intensity as %\( \dot{E}_{aero} \) max. Since \( \dot{E}_{aero} \) depends on \( \dot{V}O_2 \) and substrate oxidation, all studies should at least report \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) or RER, thereby enabling readers to calculate \( \dot{E}_{aero} \) and compare \( \dot{V}O_2 \) results to classic studies as desired.


Figure 1. Mean relative aerobic intensity as %\( \dot{V}O_2 \) max (closed symbols) and as %\( \dot{E}_{\text{aero}} \) max (open symbols) for elite race walkers on a low carbohydrate/high fat diet across four submaximal and one maximal race-walking stages (3). \( \Delta \) indicates a difference in relative intensity percentage points between the two calculation methods. Data in this figure are from Table 4 of Burke et al. (3) and \( \dot{E}_{\text{aero}} \) is determined using the reported \( \dot{V}O_2 \), RER, and a standard conversion (16). We used the energy equivalent of carbohydrates at Burke et al.’s “max” stage (16). Across walking stages, relative aerobic intensity was statistically lower using %\( \dot{E}_{\text{aero}} \) max versus %\( \dot{V}O_2 \) max (one-way ANOVA, p<0.001). The difference between %\( \dot{E}_{\text{aero}} \) max and %\( \dot{V}O_2 \) max depended on the race-walking stage (two-way ANOVA, interaction effect p=0.004) (3), indicating that %\( \dot{E}_{\text{aero}} \) max and %\( \dot{V}O_2 \) max have different slopes when plotted against workload or velocity. This figure is created with data adapted from Burke et al. (3) as per the Creative Commons Public License: https://creativecommons.org/licenses/by/4.0/legalcode.