Metabolic Computations in Open-Circuit Spirometry

STANDARDIZING GAS VOLUMES: ENVIRONMENTAL FACTORS

Gas volumes obtained during physiologic measurements are usually expressed in one of three ways: *ATPS, STPD,* or *BTPS.*

ATPS refers to the volume of gas at the specific conditions of measurement, at *A*mbient *T*emperature (273°K + ambient temperature, °C), ambient *P*ressure, and *S*aturated with water vapor. Gas volumes collected during open-circuit spirometry and pulmonary function tests are measured initially at ATPS.

A volume of a gas varies depending on its temperature, pressure, and content of water vapor, even though the absolute number of gas molecules remains constant. These environmental influences are summarized as follows:

Temperature: The volume of a gas varies *directly* with temperature. Increasing temperature causes the molecules to move more rapidly; the gas mixture expands, and the volume increases proportionately *(Charles' law).*

Pressure: The volume of a gas varies *inversely* with pressure. Increasing pressure on a gas forces the molecules closer together, causing the volume to decrease in proportion to the increase in pressure *(Boyle's law).*

Water vapor: The volume of a gas varies with its water vapor content. The volume of a gas is greater when saturated with water vapor than when the same gas is dry (i.e., contains no moisture).

These three factors—temperature, pressure, and the relative degree of saturation of the gas with water vapor—must be considered, especially when gas volumes are compared under different environmental conditions and used subsequently in metabolic and physiologic calculations. The standards that provide the frame of reference for expressing a volume of gas are either STPD or BTPS.

STPD refers to the volume of a gas expressed under *S*tandard conditions of *T*emperature (273°K or 0°C), *P*ressure (760 mm Hg), and *D*ry (no water vapor). Expressing a gas volume STPD, for example, makes it possible to evaluate and compare the volumes of expired air measured while running in the rain at high altitude, along a beach in the cold of winter, or in a hot desert environment below sea level. *In all metabolic calculations, gas volumes are always expressed at STPD.*

1. To reduce a gas volume to standard temperature (ST), the following formula is applied:

$$\text{Gas volume ST} = V_{ATPS} \times \frac{273°K}{273°K + T°C} \qquad (1)$$

where T°C = temperature of the gas in the measuring device and 273°K = absolute temperature Kelvin, which is equivalent to 0°C.

2. The following equation expresses as a gas volume at standard pressure (SP):

$$\text{Gas volume SP} = V_{ATPS} \times \frac{P_B}{760 \text{ mm Hg}} \qquad (2)$$

where P_B = ambient barometric pressure in mm Hg and 760 = standard barometric pressure at sea level, mm Hg.

3. To reduce a gas to standard dry (SD) conditions, the effects of water vapor pressure at the particular environmental temperature must be subtracted from the volume of gas. Because expired air is 100% saturated with water vapor, it is not necessary to determine its percentage saturation from measures of relative humidity. The vapor pressure in moist or completely humidified air at a particular ambient temperature can be obtained in Table D.1 and is expressed in mm Hg. This vapor pressure (P_{H_2O}) is then subtracted from the ambient

TABLE D.1 ■ **VAPOR PRESSURE (P_{H_2O}) OF MOIST GAS AT TEMPERATURES NORMALLY ENCOUNTERED IN THE LABORATORY**

T (°C)	P_{H_2O} (MM HG)	T (°C)	P_{H_2O} (MM HG)
20	17.5	31	33.7
21	18.7	32	35.7
22	19.8	33	37.7
23	21.1	34	39.9
24	22.4	35	42.2
25	23.8	36	44.6
26	25.2	37	47.1
27	26.7	38	49.7
28	28.4	39	52.4
29	30.0	40	55.3
30	31.8		

barometric pressure (P_B) to reduce the gas to standard pressure dry (SPD) as follows:

$$\text{Gas volume SPD} = V_{ATPS} \times \frac{P_B - P_{H_2O}}{760} \qquad (3)$$

By combining equations (1) and (3), any volume of moist air can be converted to STPD as follows:

$$\text{Gas volume STPD} = V_{ATPS}\left(\frac{273}{273 + T°C}\right)\left(\frac{P_B - P_{H_2O}}{760}\right) \qquad (4)$$

Fortunately, these computations need not be carried out, because appropriate *STPD correction factors* have been calculated for moist gas in the range of temperatures and pressures ordinarily encountered in most laboratories. These factors are presented in Table D.2. Multiplying any gas volume ATPS by the appropriate correction factor gives the same gas volume STPD obtained if values for ambient temperature, barometric pressure, and water vapor pressure were substituted in equation (4).

The term *BTPS* refers to a volume of a gas expressed at *Body Temperature* (usually 273°K+37°C or 310°K), ambient *Pressure* (whatever the barometer reads), and *Saturated* with water vapor with a partial pressure of 47 mm Hg at 37°C. Conventionally, pulmonary physiologists express lung volumes such as vital capacity, inspiratory and expiratory capacity, residual lung volume, and the dynamic measures of lung function such as maximum breathing capacity at body temperature and moist, or BTPS. The following equation converts a gas volume ATPS to BTPS:

$$\text{Gas volume} \atop \text{(BTPS)} = V_{ATPS}\left(\frac{P_B - P_{H_2O}}{P_B - 47 \text{ mm Hg}}\right)\left(\frac{310}{273 + T°C}\right) \qquad (5)$$

As was the case with the correction to STPD, appropriate BTPS *correction factors* are available for converting a moist gas volume at ambient conditions to a volume BTPS. These BTPS factors for a broad range of ambient temperatures are

TABLE D.2 ■ FACTORS TO REDUCE MOIST GAS TO A DRY GAS VOLUME AT 0°C AND 760 mm Hg

BAROMETRIC READING	TEMPERATURE (°C)																	
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
700	0.855	851	847	842	838	834	829	825	821	816	812	807	802	797	793	788	783	778
702	857	853	849	845	840	836	832	827	823	818	814	809	805	800	795	790	785	780
704	860	856	852	847	843	839	834	830	825	821	816	812	807	802	797	792	787	783
706	862	858	854	850	845	841	837	832	828	823	819	814	810	804	800	795	790	785
708	865	861	856	852	848	843	839	834	830	825	821	816	812	807	802	797	792	787
710	867	863	859	855	850	846	842	837	833	828	824	819	814	809	804	799	795	790
712	870	866	861	857	853	848	844	839	836	830	826	821	817	812	807	802	797	792
714	872	868	864	859	855	851	846	842	837	833	828	824	819	814	809	804	799	794
716	875	871	866	862	858	853	849	844	840	835	831	826	822	816	812	807	802	797
718	877	873	869	864	860	856	851	847	842	838	833	828	824	819	814	809	804	799
720	880	876	871	867	863	858	854	849	845	840	836	831	826	821	816	812	807	802
722	882	878	874	869	865	861	856	852	847	843	838	833	829	824	819	814	809	804
724	885	880	876	872	867	863	858	854	849	845	840	835	831	826	821	816	811	806
726	887	883	879	874	870	866	861	856	852	847	843	838	833	829	824	818	813	808
728	890	886	881	877	872	868	863	859	854	850	845	840	836	831	826	821	816	811
730	892	888	884	879	875	871	866	861	857	852	847	843	838	833	828	823	818	813
732	895	890	886	882	877	873	868	864	859	854	850	845	840	836	831	825	820	815
734	897	893	889	884	880	875	871	866	862	857	852	847	843	838	833	828	823	818
736	900	895	891	887	882	878	873	869	864	859	855	850	845	840	835	830	825	820
738	902	898	894	889	885	880	876	871	866	862	857	852	848	843	838	833	828	822
740	905	900	896	892	887	883	878	874	869	864	860	855	850	845	840	835	830	825
742	907	903	898	894	890	885	881	876	871	867	862	857	852	847	842	837	832	827
744	910	906	901	897	892	888	883	878	874	869	864	859	855	850	845	840	834	829
746	912	908	903	899	895	890	886	881	876	872	867	862	857	852	847	842	837	832
748	915	910	906	901	897	892	888	883	879	874	869	864	860	854	850	845	839	834
750	917	913	908	904	900	895	890	886	881	876	872	867	862	857	852	847	842	837
752	920	915	911	906	902	897	893	888	883	879	874	869	864	859	854	849	844	839
754	922	918	913	909	904	900	895	891	886	881	876	872	867	862	857	852	846	841
756	925	920	916	911	907	902	898	893	888	883	879	874	869	864	859	854	849	844
758	927	923	918	914	909	905	900	896	891	886	881	876	872	866	861	856	851	846
760	930	925	921	916	912	907	902	898	893	888	883	879	874	869	864	859	854	848
762	932	928	923	919	914	910	905	900	896	891	886	881	876	871	866	861	856	851
764	936	930	926	921	916	912	907	903	898	893	888	884	879	874	869	864	858	853
766	937	933	928	924	919	915	910	905	900	896	891	886	881	876	871	866	861	855
768	940	935	931	926	922	917	912	908	903	898	893	888	883	878	873	868	863	858
770	942	938	933	928	924	919	915	910	905	901	896	891	886	881	876	871	865	860

TABLE D.3 ■ BTPS[a] CORRECTION FACTORS			
T (°C)	BTPS	T (°C)	BTPS
20	1.102	29	1.051
21	1.096	30	1.045
22	1.091	31	1.039
23	1.085	32	1.032
24	1.080	33	1.026
25	1.075	34	1.020
26	1.068	35	1.014
27	1.063	36	1.007
28	1.057	37	1.000

[a]Body temperature, ambient pressure, and saturated with water vapor.

presented in Table D.3. The factors have been computed assuming a barometric pressure of 760 mm Hg, and small deviations ($\pm$10 mm Hg) from this pressure introduce only a minimal error.

CALCULATION OF OXYGEN CONSUMPTION

In determining oxygen consumption by open-circuit spirometry, we are interested in knowing how much oxygen has been removed from the *inspired air*. Because the composition of inspired air remains relatively constant (CO_2 = 0.03%, O_2 = 20.93%, N_2 = 79.04%), it is possible to determine the oxygen removed from the inspired air by measuring the amount and composition of the expired air. This measurement indicates that the expired air contains more carbon dioxide (usually 2.5 to 5.0%), less oxygen (usually 15.0 to 18.5%), and more nitrogen (usually 79.04 to 79.60%). However, nitrogen is inert in terms of metabolism; any change in its concentration in expired air reflects the fact that the number of oxygen molecules removed from the inspired air is not replaced by the same number of carbon dioxide molecules produced in metabolism. This results in the volume of expired air (V_E, STPD) being unequal to the inspired volume (V_I, STPD). For example, if the respiratory quotient is less than 1.00 (i.e., less CO_2 produced in relation to O_2 consumed), and 3 liters of air are inspired, *less* than 3 liters of air will be expired. This produces a higher nitrogen concentration in expired air than in inspired air. This is not to say that nitrogen has been produced, only that nitrogen molecules now represent a larger percentage of V_E compared to V_I. In fact, V_E differs from V_I in direct proportion to the change in nitrogen concentration between the inspired and expired volumes. Thus, V_I can be determined from V_E using the relative change in nitrogen in an equation known as the *Haldane transformation*.

$$V_I, \text{STPD} = V_E, \text{STPD} \times \frac{\%N_2E}{\%N_2I} \qquad (6)$$

where $\%N_2I$ = 79.04 and $\%N_2E$ = percentage nitrogen in expired air computed from gas analysis as $[(100 - (\%O_2E + \%CO_2)]$.

The volume of O_2 in the inspired air ($V_{O_2}I$) can then be determined as follows:

$$V_{O_2}I = V_I \times \%O_2I \qquad (7)$$

Substituting equation (6) for V_I,

$$V_{O_2}I = V_E \times \frac{\%N_2E}{79.04\%} \times \%O_2I \qquad (8)$$

where $\%O_2I$ = 20.93%

The amount or volume of oxygen in the expired air ($V_{O_2}E$) is computed as

$$V_{O_2}E = V_E \times \%O_2E \qquad (9)$$

where $\%O_2E$ is the fractional concentration of oxygen in expired air determined by gas analysis (chemical or electronic methods).

The amount of O_2 removed from the inspired air *each minute* ($\dot{V}_{O_2}$) can then be computed as follows:

$$\dot{V}_{O_2} = (\dot{V}_I \times \%O_2I) - (\dot{V}_E \times \%O_2E) \qquad (10)$$

By substitution

$$\dot{V}_{O_2} = \left\{ \left[\left(\dot{V}_E \times \frac{\%N_2E}{79.04\%} \right) \times 20.93\% \right] - (\dot{V}_E \times \%O_2E) \right\} (11)$$

where $\dot{V}_{O_2}$ = volume of oxygen consumed per minute, expressed in milliliters or liters, and $\dot{V}_E$ = expired air volume per minute expressed in milliliters or liters.

Equation (11) can be simplified to:

$$\dot{V}_{O_2} = \dot{V}_E \left[\left(\frac{\%N_2E}{79.04\%} \times 20.93\% \right) - \%O_2E \right] \qquad (12)$$

The final form of the equation is:

$$\dot{V}_{O_2} = \dot{V}_E [(\%N_2E \times 0.265) - \%O_2E] \qquad (13)$$

The value obtained within the brackets in equations (12) and (13) is referred to as the *true O_2*; this represents the "oxygen extraction" or, more precisely, the percentage of oxygen consumed for any volume of air *expired*.

Although equation (13) is the equation used most widely to compute oxygen consumption from measures of expired air, it is also possible to calculate $\dot{V}_{O_2}$ from direct measurements of both $\dot{V}_I$ and $\dot{V}_E$. In this case, the Haldane transformation is not used, and oxygen consumption is calculated directly as:

$$\dot{V}_{O_2} = (\dot{V}_I \times 20.93) - (\dot{V}_E \times \%O_2E) \qquad (14)$$

In situations in which only $\dot{V}_I$ is measured, the $\dot{V}_E$ can be calculated from the Haldane transformation as:

$$\dot{V}_E = \dot{V}_I \frac{\%N_2I}{\%N_2E}$$

By substitution in equation (14), the computational equation is:

$$\dot{V}_{O_2} = \dot{V}_I \left[\%O_2I - \left(\frac{\%N_2I}{\%N_2E} \times \%O_2E \right) \right] \qquad (15)$$

CALCULATION OF CARBON DIOXIDE PRODUCTION

Carbon dioxide production per minute ($\dot{V}_{CO_2}$) is calculated as follows:

$$\dot{V}_{CO_2} = \dot{V}_E(\%CO_2E - \%CO_2I) \qquad (16)$$

where $\%CO_2E$ = percentage carbon dioxide in expired air determined by gas analysis, and $\%CO_2I$ = percentage carbon dioxide in inspired air, which is essentially constant at 0.03%.

The final form of the equation is:

$$\dot{V}_{CO_2} = \dot{V}_E(\%CO_2E - 0.03\%) \qquad (17)$$

CALCULATION OF RESPIRATORY QUOTIENT

The respiratory quotient (RQ) is calculated in one of two ways:

1. $RQ = \dot{V}_{CO_2}/\dot{V}_{O_2}$ (18)

    or

2. $RQ = \dfrac{(\%CO_2E - 0.03\%)}{\text{"true" } O_2}$ (19)

SAMPLE METABOLIC CALCULATIONS

The following data were obtained during the last minute of a steady-rate, 10-minute treadmill run performed at 6 miles per hour at a 5% grade.

> $\dot{V}_E$: 62.1 liters, ATPS
> Barometric pressure: 750 mm Hg
> Temperature: 26°C
> $\%O_2$ expired: 16.86 (O_2 analyzer)
> $\%CO_2$ expired: 3.60 (CO_2 analyzer)
> $\%N_2$ expired: $[100 - (16.86 + 3.60)] = 79.54$

Determine the following:

> 1. $\dot{V}_E$, STPD
> 2. $\dot{V}_{O_2}$, STPD
> 3. $\dot{V}_{CO_2}$ STPD
> 4. RQ
> 5. kCal $\cdot$ min^{-1}

1. $\dot{V}_E$, STPD (use equation 4 or STPD correction factor in Table D.2).

$$\dot{V}_E, \text{STPD} = \dot{V}_E, \text{ATPS} \left(\frac{273}{273 + T°C}\right)\left(\frac{P_B - P_{H_2O}}{760}\right)$$

$$= 62.1 \left(\frac{273}{299}\right)\left(\frac{750 - 25.2}{760}\right)$$

$$= 62.1 \, (0.913 \times 0.954)$$
$$= 54.07 \, L \cdot min^{-1}$$

2. $\dot{V}_{O_2}$, STPD (use equation 13)

$$\dot{V}_{O_2}, \text{STPD} = \dot{V}_E, \text{STPD} [(\%N_2E \times 0.265) - \%O_2E]$$
$$= 54.07 \, [(0.7954 \times 0.265) - 0.1686]$$
$$= 54.07 \, (0.0422)$$
$$= 2.281 \, L \cdot min^{-1}$$

3. $\dot{V}_{CO_2}$, STPD (use equation 17)

$$\dot{V}_{CO_2}, \text{STPD} = \dot{V}_E, \text{STPD} \, (\%CO_2E - 0.03\%)$$
$$= 54.07 \, (0.0360 - 0.0003)$$
$$= 54.07 \, (0.0357)$$
$$= 1.930 \, L \cdot min^{-1}$$

4. RQ (use equation 18 or 19)

$$RQ = \dot{V}_{CO_2}/\dot{V}_{O_2}$$
$$= \frac{1.930 \, L \, CO_2 \cdot min^{-1}}{2.281 \, L \, O_2 \cdot min^{-1}}$$
$$= 0.846$$

or

$$RQ = \frac{(\%CO_2E - 0.03\%)}{\text{"true" } O_2}$$
$$= \frac{3.60 - .03}{4.22}$$

Because the exercise was performed in a steady rate of aerobic metabolism, the obtained RQ of 0.846 can be applied in Table 8.1 to obtain the appropriate caloric transformation. In this way, the exercise oxygen consumption can be transposed to kCal of energy expended per minute as follows:

5. Energy expenditure (kCal $\cdot$ min^{-1}) = $\dot{V}_{O_2}$ (L $\cdot$ min^{-1}) × caloric equivalent per liter O_2 at the given steady-rate RQ

$$\text{Energy expenditure} = 2.281 \times 4.862$$
$$= 11.09 \, kCal \cdot min^{-1}$$

Assuming that the RQ value reflects the nonprotein RQ, a reasonable estimate of both the percentage and quantity of lipid and carbohydrate metabolized during each minute of the run can be obtained from Table 8.1.

Percentage kCal derived from lipid = 50.7%
Percentage kCal derived from carbohydrate = 49.3%
Grams of lipid utilized = 0.267 g per liter of oxygen or approximately 0.61 g per minute (0.267 × 2.281 L O_2)
Grams of carbohydrate utilized = 0.580 g per liter of oxygen or approximately 1.36 g per minute (0.580 × 2.281 L O_2)