Appendix E   Symbols and Units: Toward Standardization

E. Gnaiger[1]

Table 1. Selected SI Base Units (a), SI Derived Units (b), and units in use with the International System (c) [6]

(a)			(b)			(c)		
Symbol	Name	Physical quantity	Symbol	Name	Physical quantity	Symbol	Name	Physical quantity
m	metre	l, h, z, δ	Pa	pascal	$p, p_{O_2}, {}_b p$	h	hour	t
kg	kilogram	$W, {}_w W, {}_d W$	J	joule	Q	min	minute	t
s	second	t	W	watt	$P, \dot{Q}$	°C	degree	
A	ampere	I	C	coulomb	e		Celsius	θ
K	kelvin	T	V	volt	U	bar	bar	p
mol	mole	n, N	Ω	ohm	R			

In attempting to combine the expertise of specialists in various disciplines under the title of polarographic oxygen measurement, it became necessary to reach conformity as to the usage of different terms, units, and symbols. Despite the recommendations periodically published by international committees as to what constitutes a standardized scientific terminology [3, 5, 6], agreement is rather poor. Interdisciplinary communication and clarity in the documentation of scientific literature can be improved by a stricter adherance to the fundamental guidelines at present available. Some conflicting terms and some apparently problematic units are discussed briefly in the following.

"Polarographic oxygen sensor" (POS) has been proposed instead of the term "oxygen electrode" [1]. "Electrode" is reserved for "half cell" and should not be confused with the set of two electrodes making up the unit of a POS. The term "oxygen electrode" is retained only if the oxygen reducing cathode and the reference electrode are employed separately (Chap. III.2).

A basic quantity related to the signal of a POS is the partial pressure of oxygen (symbol: p_{O_2}, although subscripts to subscripts should be avoided where possible). The SI unit for pressure is the pascal (1 Pa = 1 N m^{-2}) (Table 1). Although the bar (1 bar = 10^5 Pa) is also retained for the time being, it does not belong to the International System of Units. The use of the torr (symbol: Torr) and the conventional millimeter of mercury (symbol: mmHg; the mmHg differs from the Torr by less than 2×20^{-7} Torr) "is to be progressively discouraged and eventually abandoned" [6].

Another basic quantity relevant to POS is the permeability coefficient, and two permeability coefficients of different dimensions, P and P, have been defined: if the standard states are carefully chosen, these are numerically identical (Chap. I.3). In the physiological literature the product $D \times S =$ P has been termed Krogh's constant of diffusion (where S includes physical solubility and chemical binding of a gas in a liquid), while D/δ is usually called "permeability" [8]. The latter term is particularly ambiguous if applied to a membrane separating compartments of different solubility (as is the case in POS and usually in cellular systems). In this case the effect that solubility and solubility changes along the diffusion path exerts on the diffusion impedance is ignored (Chaps. I.1, I.3).

1 Institut für Zoologie, Abteilung Zoophysiologie, Universität Innsbruck, Peter-Mayr-Str. 1A, A–6020 Innsbruck, Austria

The POS is most frequently applied for measurement of oxygen concentration, i.e., amount of oxygen divided by the volume of the solution or mixture. The SI Base Unit relating to amount of substance (oxygen), N_{O_2}, is the mole (symbol: mol) (Table 1). The SI Unit relating to volume, V, is the cubic metre (symbol: m^3). Instead of the proper unit for V, the litre is still found predominantly (1 l = 1 dm^3; 1 ml = 1 cm^3; 1 μl = 1 mm^3), although neither the word litre nor its symbol should be used [6]. The basic quantity for oxygen concentration is therefore the "amount-of-substance concentration" of oxygen, $c_{O_2} = N_{O_2} \times V^{-1}$, with units [mol m^{-3}] which may be used with any SI prefix, e.g., 1 μmol dm^{-3} = 10^3 mol m^{-3}. Frequently, oxygen concentration is given in cm^3 O$_2$ dm^{-3} (relating to the units of the Bunsen absorption coefficient, α). In limnology and oceanography the use of mass concentration, ρ_{O_2} [mg dm^{-3}] is still very common. However, c_{O_2} should always be given in units [mol m^{-3}]. For conversion of units see App. A, Table 6.

The conceptual advantage of expressing basic quantities in gas exchange physiology in terms of molar units was convincingly outlined in 1971 [8]. However, this was neglected by most respiratory physiologists and even by a physiological Committee on Nomenclature which, two years later [4], again recommended volume units for expressing oxygen consumption, $\dot{V}_{O_2}$ [cm^3 h^{-1}]. Many ecological physiologists express oxygen uptake rates in [mg h^{-1}], and a confusing variety of symbols exists. The proper symbol for "molar oxygen uptake rate" is $\dot{N}_{O_2} = dN_{O_2} \times dt^{-1}$ (or often more strictly $\Delta N_{O_2} \times \Delta t^{-1}$) [nmol s^{-1} or μmol h^{-1}]. In the steady state (of a POS or an organism) the reduction of the external amount of oxygen is equal to the internal (electrochemical or metabolic) conversion of oxygen. If the internal oxygen store changes (nonsteady state, e.g., Chap. II.4) the oxygen consumption rate should be distinguished from the oxygen flux through the oxygen transducing area, $J_{O_2} \times A$ (with the same units as $\dot{N}_{O_2}$). For conversion of units see App. C, Table 2.

Oxygen consumption rates can be converted to rates of heat dissipation, $\dot{Q}$ [mW] (Chaps. II.3, II.4). The joule is progressively replacing the calorie. The symbol $\Delta_k H_{O_2}$ [kJ mol^{-1}] is used for the oxycaloric equivalent expressing the enthalpy change per mole of oxygen consumed in dissipative metabolism (App. C). The subscript k designates the "catabolic half cycle" [2]; dissipative metabolism corresponds to the metabolic state when net energy liberated in the sequence of reactions in the catabolic half cycle is neither conserved in catabolic energy coupling nor in anabolism. In a recent

recommendation on biothermodynamic nomenclature [5] "catabolism" was confused with the "catabolic half cycle", thus neglecting that "catabolism and anabolism consist of two simultaneous and interdependent processes which may be analyzed separately" [7]. The enthalpy equivalent of catabolism may vary with the degree of energy-coupling and net accumulation of "high-energy intermediates" [2]. Any ambiguity is avoided in the term $\Delta_k H_{O_2}$ as defined above. Since thermochemical quantities are usually expressed on a mole basis, this practice should be adopted for the oxycaloric equivalent. For conversion factors see App. C, Table 3.

In addition to the obvious advantage of using the generally applicable unit "mole" in quantities involving "amount of oxygen", the adoption of the mole simplifies expressions and calculations of stoichiometric, i.e., molecular relationships (e.g., App. C). This may encourage functional interpretations of oxygen consumption measurements and contribute to an alignment of concepts in bioenergetic ecology, respiratory physiology, biochemistry and biothermodynamics. Several ad hoc symbols encountered in the physiological literature (e.g, $\sim P/O$ ratio, RQ, NQ) can be replaced by commonly accepted stoichiometric coefficients, ν, which are unambiguously understood in a wider interdisciplinary context (Table 2, pp. 355–358).

References

1. Fatt I (1976) Polarographic oxygen sensors. CR C Press, Cleveland, p 2
2. Gnaiger E (1980) Das kalorische Äquivalent des ATP-Umsatzes im aeroben und anoxischen Metabolismus. Thermochim Acta 40:195–223
3. Weast RC (ed) (1974–75) Handbook of chemistry and physics, 55th edn. CR C Press, Cleveland
4. International Union of Physiological Sciences (1973) Glossary on respiration and gas exchange. Prepared for publication by Bartels H, Dejours P, Kellogg RH, Mead J. J Appl Physiol 34:549–558
5. Interunion Commission on Biothermodynamics (IUPAC, IUB, IUPAB) (1982) Calorimetric measurements on cellular systems. Recommendations for measurements and presentation of results. Prepared by Belaich JP, Beezer AE, Prosen E, Wadsö I. Pure Appl Chem (in press)
6. IUPAC (1979) Manual of symbols and terminology for physicochemical quantities and units. Prepared for publication by Whiffen DH. Pergamon Press, Oxford, 41 pp
7. Lehninger AL (1975) Biochemistry. Woerth Publ, New York
8. Piiper J, Dejours P, Haab P, Rahn H (1971) Concepts and basic quantities in gas exchange physiology. Respir Physiol 13:292–304

Table 2. List of symbols, description and corresponding units following the IUPAC recommendations [6]. Only symbols frequently used in the text or relevant to POS are listet. When the same symbol is used with different subscripts, then these are not explained separately. The subscripts are: a air; b barometric (in $_b p$); b blood; e electrolyte; h actual or total (pressure as a function of water depth h); m membrane (in V_m: molar); s sample medium; w hydrostatic (pressure of water column). Page numbers refer to the text where the respective symbol is used, pages in italics refer to tables or figures

Symbol	Description and units	Page
a_{O_2}	$= y_{O_2} \times c_{O_2}/c^\circ_{O_2} = f_{O_2}/f^\circ_{O_2}$; relative activity of oxygen, concentration based; a_m, a_s	4, 31ff., *33*
A	area [m²]	5ff., 18f., 28, 34, *39, 45,* 77, *80*
c_{O_2}	$= N_{O_2} \times V^{-1} = p_{O_2} \times S_{O_2}$; amount-of-substance concentration of oxygen [μmol dm⁻³]; c_a, c_b, c_e, c_m, c_s	15, 18, 23, 27f., 32ff., *104,* 112, 114, 123, 146ff., 153f., *154, 160,* 215, *224,* 227, *250f., 254ff.,* 277
$c^\circ_{O_2}$	standard concentration of oxygen, 1 mol dm⁻³; c°_m, c°_s	4, 32ff.
$C*$	unit standard concentration of oxygen (molar concentration) [μmol dm⁻³]	322ff., *331*
$C^\dagger$	unit standard concentration of oxygen (molal concentration) [μmol kg⁻¹]	322f.
C_c	saturation concentration of oxygen as a function of temperature, salinity and barometric pressure [μmol dm⁻³]	325, 327ff., *330f.*
D_m	diffusion coefficient of oxygen in the membrane [m² s⁻¹]; D_a (20°C) = 3 × 10⁻⁵ m² s⁻¹; D_e (25°C) = 2 × 10⁻⁹ m² s⁻¹; D_s	5ff., *6,* 11, 15, 19, 23f., 28, 32ff., 50f., 56, *57,* 77, 238f.
e	elementary charge, 1.60219 × 10⁻¹⁹ C	8
E°	electromotive force	22, 66, 68, 73, *74*
f	$= dV \times dt^{-1}$; flow rate [cm³ s⁻¹ or cm³ h⁻¹]	112, 148, 150, 153
f_{O_2}	fugacity of oxygen [kPa]	4f., 7f., 19
F	$= L \times e$; Faraday constant, 96485 C mol⁻¹ or As mol⁻¹	5ff., 18f., 28, 34, 56
F_c	calibration factor of a POS, concentration based [μmol dm⁻³ μA⁻¹]	147f.
F_p	calibration factor of a POS, partial pressure based [kPa μA⁻¹]	146
g_n	standard acceleration of free fall, 9.80665 m s⁻²	328f.
ΔG°	difference or change in molar standard Gibbs energy [kJ mol⁻¹]	32
h	height or depth [m]	123, *124,* 326, *328f.*
$\Delta_c h$	specific enthalpy of combustion [kJ g⁻¹]	*340, 343*
$\Delta_k H_{O_2}$	molar caloric equivalent of respiratory oxygen consumption in dissipative metabolism [kJ mol⁻¹]	*160f., 163,* 167, *340ff., 343f.*
I_1	electric current, diffusion limited signal of a POS [μA], proportional to A (large cathode) or to r_o (microcathode)	5ff., *8,* 18ff., *20,* 34, 44f., *45f., 51, 54f.,* 56, 77, *78,* 93ff., 105, 146ff., 215

Table 2 (continued)

Symbol	Description and units	Page
I_{O_2}	$= I_l - I_r$; oxygen current of a POS, signal corrected for the residual current [μA]	146
I_r	residual (zero) current of a POS in an oxygen free medium [μA]	15, 46, 146ff.
I_r	radial diffusion current [μA]	27f.
J_{O_2}	flux of oxygen [mol m^{-2} s^{-1}]	5, 32ff., 236, 238, *281f.*
k	$= R \times L^{-1}$; Boltzmann constant, 1.3807×10^{-23} J K^{-1}	*357*
k_s	Henrys law constant [kPa]	36
K	equilibrium constant or distribution coefficient	32ff., 73
l	length [m]	23f., 123, *124*
L	Avogadro constant, 6.0220×10^{23} mol^{-1}	*355*
M_r	relative molecular mass of a substance; M_r (O$_2$) = 31.9988	328f.
n	charge number of a cell reaction, number of electrones added to each oxygen molecule at the cathode	5ff., 18f., 34, 56
N_{O_2}	molar amount of oxygen [mol]	148, 153f., 226f., *329*
$\dot{N}_{O_2}$	$= dN_{O_2} \times dt^{-1}$; molar oxygen uptake rate [nmol s^{-1} or μmol h^{-1}]	112, 123, 148, *213ff.,* 277, *344*
$\dot{N}_{O_2}^o$	reference (blank) rate of oxygen consumption [nmol s^{-1} or μmol h^{-1}]	*149*
$\dot{n}_{O_2}$	$= dN_{O_2} \times dt^{-1} \times W^{-1}$; specific rate of oxygen consumption [nmol s^{-1} g^{-1} or μmol h^{-1} g^{-1}]	114, *124, 137, 156ff.*
NQ	$= \nu_{N/O_2}$; nitrogen quotient [moles N in excretory products per mole O$_2$]	338ff., *340ff.*
p	pressure [kPa] (1 Pa = 1 N m^{-2}; 1 bar = 100 kPa; 1 mmHg = 0.133322 kPa; 1 atm = 101.325 kPa; 1 m H$_2$O = 9.80638 kPa; 1 psi = 6.89 kPa; 1 inchHg = 3.38 kPa)	*85,* 325
p_o	$= 1$ atm = 101.325 kPa; normal atmosphere, standard atmospheric (barometric) pressure	322, 324ff.
$_bp$	barometric (atmospheric) pressure [kPa]	*106, 238,* 325ff., *328,* 334ff.
p_h	$= {_bp} + {_wp}$; actual (total) pressure at water depth h [kPa]	326f.
$_wp$	hydrostatic pressure under a column of water [kPa]; 1 m H$_2$O = 0.09678 atm = 9.80638 kPa at 4°C	12, *144,* 326ff.
p_A	$= x_A \times p$; partial pressure of gas A [kPa]; p_{N_2}; p_X	327, 334f.
p_{H_2O}	water vapor pressure at experimental temperature [kPa]	322, 324ff., *328,* 334ff.
p_{O_2}	partial pressure of oxygen; nearly identical to f_{O_2} for oxygen pressures $< p_o$ [kPa]; p_b, p_m, p_s	18, 34ff., 47, *54f.,* 56, *59ff.,* 77, *104f.,* 130, 146, *149,* 168, *172f., 222, 224,* 226f., 236, *238ff.,* 325, 327f., *329,* 334f.

Table 2 (continued)

Symbol	Description and units	Page
$p_{O_2,c}$	critical (saturation) partial pressure of oxygen as a function of barometric and hydrostatic pressure [kPa]	327
P	$= dQ \times dt^{-1}$; power [μW]	
P_m	$= S_m \times D_m$; permeability coefficient of the membrane, based on unit partial pressure [mol m^{-1} s^{-1} kPa^{-1}]; P_e, P_s	31ff., 49f., *50, 57,* 77
P_m	$= K \times D_m$; permeability coefficient of the membrane, based on unit activity [m^2 s^{-1}]; P_e, P_s	18, 24, 31ff.
POS	polarographic oxygen sensor	
Q	heat [J], a positive sign indicates increase of heat of the system under discussion	*159*
$\dot{Q}$	$= dQ \times dt^{-1}$; power, rate of heat dissipation [1 J s^{-1} = 1 W] a negative sign indicates heat dissipation out of the system under discussion (inaccurately called "heat production")	*161ff.,* 340, *344*
$\dot{q}$	$= dQ \times dt^{-1} \times W^{-1}$; specific rate of heat dissipation [mW g^{-1}]	*159f.*
r_E	horizontal distance from the center of the electrode (cathode) [m]	47, *48*
r_o	radius of the cathode [m]	27f., 45, 47, *48ff., 80, 266*
R	$= K \times L$; gas constant, 8.31441 ± 0.00026 J K^{-1} mol^{-1}	*8, 12, 31f., 36,* 328f.
R	electrical resistance [Ω]	*91,* 93ff., *95, 98f., 101, 180, 251*
RQ	$= \nu_{CO_2/O_2}$; respiratory quotient or respiratory gas exchange ratio [moles CO$_2$ per mole O$_2$]	337ff., *340ff.*
S_s	solubility of oxygen in the sample medium [μmol dm^{-3} kPa^{-1}]; S_s (pure water, 25°C) = 12.5 μmol dm^{-3} kPa^{-1}; S_e (1.5 mol dm^{-3} KCl, 25°C) = 8.5 μmol dm^{-3} kPa^{-1}; S_m	5, *6ff.,* 19, 34ff., *50,* 56, *57,* 77, *104,* 146, *204,* 226f., 236, 238f., 322ff.
STPD	standard temperature (T_o = 273.15 K = 0°C) and pressure (p_o = 101.325 kPa = 1 atm), dry	
t	time [s or min or h]	112, 114, 123, 153f.
T	thermodynamic (absolute) temperature [K]	8, 12, 31f., 36, 95ff., 105, 252, 323f., 326, 328f., 334
T_o	zero of the Celsius scale, standard temperature, 273.15 K	
U	$= I \times R$; electric potential difference [V]	8, 46, 93ff., *147, 161, 172f., 251*
V	volume [m^3]	112, 114, 123, 153f., 168, 226, *230, 251*
V_o	$= R \times T_o \times p_o^{-1}$; standard molar volume of ideal gas, 22.41383 ± 0.00070 dm^3 mol^{-1}	*329*
V_m	molar volume at STP; V_m (O$_2$) = 22.392 dm^3 mol^{-1}	11, *329*
$\dot{V}_{O_2}$	$= dV_{O_2} \times dt^{-1}$; volume based oxygen consumption [mm^3 h^{-1}]	168, *182*

Table 2 (continued)

Symbol	Description and units	Page
w_i	mass fraction of compound i	338f., 342f.
W	weight [g]; $_dW$ dry weight; $_wW$ wet weight	114, *137*, 150, 338, *339f., 344*
x_i	mole fraction of compound i	338, 341f., 344
y_{O_2}	activity coefficient of oxygen defined in terms of amount-of-substance concentration; y_m, y_s	4, 32ff.
z_m	thickness of the membrane [m]; z_e, z_s	5, *6ff.*, 18f., 24, 28, *33ff., 48ff., 50*, 77, 236, *238f.*
z_m/P_m	diffusion impedance or mass transfer impedance of the membrane [m^2 s kPa mol^{-1}]	*6*, 77
α	Bunsen absorption coefficient, solubility [cm^3 cm^{-3} atm^{-1}]	57, 322
δ	thickness of diffusion layer [m]; $\delta_s = z_s$	24
θ	Celsius temperature [°C]	96, *137*, 168, *204, 250, 254ff., 323, 336*
μ	chemical potential [kJ mol^{-1}]; μ_m; μ_s	31f., 36
ν_{CO_2}	stoichiometric coefficient for carbon dioxide (positive for carbon dioxide as a product)	337
ν_{O_2}	stoichiometric coefficient of oxygen (negative for oxygen as a substrate)	337
ν_{CO_2/O_2}	$= -\nu_{CO_2}/\nu_{O_2}$; respiratory gas exchange ratio or respiratory quotient, RQ	337
ν_{H^+/O_2}	$= -\nu_{H^+}/\nu_{O_2}$; hydrogen ion-oxygen exchange ratio	341
ν_{N/O_2}	$= -\nu_{NH_3}/\nu_{O_2}$; or $= -2 \times \nu_{CO(NH_2)_2}/\nu_{O_2}$; nitrogen-oxygen exchange ratio or nitrogen quotient, NQ	338
ν_s	kinematic viscosity of the sample fluid [m^2 s^{-1}]	5, 7, 27
ρ_o	density at standard temperature [mg dm^{-3}]	328
ρ_{O_2}	mass concentration of oxygen [mg dm^{-3}], compare c_{O_2}	*254ff., 278, 280*
ϕ_A	volume fraction of gas A	*20, 149, 157, 271f., 334ff.*
$\phi_{O_2}^*$	volume fraction of oxygen in dry air, 0.20946	322, 327, *328, 334ff.*
τ	time constant, response time [s or min or h]	15, 52, *78, 80*, 153, *154f., 192*