The use of SI units in cardiovascular studies¹

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The International System of units (SI) in its present form was adopted as a primary system of measurement by the General Conference of Weights and Measures (CGPM) in 1971 and it represents the most recent phase in the evolution of a rational system for the quantification of scientific data. It has its roots in the metric system and has already been adopted as the only legally acceptable system of measurement in nearly thirty countries. In essence, the system accepts only one unit for any one physical quantity. Thus, seven base units (see later) are used for the measurement of length, mass, time, electric current, thermodynamic temperature, luminous intensity, and the amount of substance. Any other unit used in science and technology can be derived from these base units without the incorporation of arbitrary numerical factors.

These aspects of the problems are illustrated in the derivation of an SI unit of force which is expressed as *mass x acceleration*. The basic SI units for mass, length, and time are the kilogram, the metre, and the second, respectively. Thus velocity will be expressed as metre per second and acceleration (which is the rate of change of velocity) as metre per second per second. Therefore, the SI unit of force will be that force which, when applied to a mass of *one* kilogram, will produce in *one* second an increase in velocity of *one* metre per second. This force is called the newton. Thus the only numerical factor involved in the derivation of this unit is unity: and larger or smaller forces can be expressed by prefixes representing 10 raised to multiples of the power 3. These procedures eliminate the use of somewhat arbitrary multiples and submultiples in the conventional British system, e.g. 16 ounces = 1 pound; 746 watts = 1 horse power.

Summary of SI units

The International System of Units recognizes three classes of units:

- (i) Base units
- (ii) Supplementary units
- (iii) Derived units.

(i) Base units

The International System is founded on seven base units listed below in Table 1.

TABLE 1

Quantity	Name of base unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

(ii) Supplementary units

Supplementary units are those units which have not yet been classified either into base units or derived units and are shown in Table 2.

TABLE 2

Quantity	Name of supplementary unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

(iii) Derived units

This third category includes all other units used in scientific work and includes two main subgroups.

- (a) This subgroup includes derived units which are denoted by names having their origin in proper names. These units in addition to being expressed in terms of base or supplementary SI units (Table 3A) will also have special names and symbols.
- (b) Derived units which are expressed algebraically

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in terms of the base (or supplementary) units and the symbols for such units incorporate the mathematical symbols for multiplication or division, e.g. the SI unit for velocity is metre per second (m/s) (Table 3B). For convenience, certain units which are derived from units listed in Table 3A above have also been included in that category, e.g. stress is denoted by newton per square metre ($\text{N}\cdot\text{m}^{-2}$).

It is clearly not practical to compile a complete list of derived units, but a list of units commonly employed in cardiovascular studies is shown in

TABLE 3

A. Named derived units			
Quantity	Name of derived unit	Symbol	Expression in terms of base units
Frequency	hertz	Hz	1 Hz = 1/s
Force	newton	N	1 N = 1 kg · m/s ²
Pressure	pascal	Pa	1 Pa = 1 N · m ⁻²
Work, energy, quantity of heat	joule	J	1 J = 1 N · m
Power	watt	W	1 W = 1 J/s
Quantity of electricity	coulomb	C	1 C = 1 A · s
Electrical potential, potential difference, electromotive force	volt	V	1 V = W · A ⁻¹
Electric capacitance	farad	F	1 F = 1 A · s · V ⁻¹
Electric resistance	ohm	Ω	1 Ω = 1 V · A ⁻¹
Electric conductance	siemens	S	1 A = 1 Ω ⁻¹
B. Other derived units			
Quantity	SI units	Symbol or definition	
Area	square metre	m ²	
*Volume	cubic metre	m ³	
†Density	kilogram per cubic metre	kg · m ⁻³	
Velocity	metre per second	m/s	
Acceleration	metre per second per second	m/s ²	
Kinematic viscosity	square metre per second	m ² /s	
Dynamic viscosity	pascal second	Pa · s	
‡Specific heat	joule per kilogram kelvin	J · kg ⁻¹ · K ⁻¹	
‡Thermal conductivity	watt per metre kelvin	W · m ⁻¹ · K ⁻¹	
Molality	mole per kilogram	mol · kg ⁻¹	
Concentration	mole per cubic decimetre	mol · dm ⁻³	
Stress	newton per square metre	N · m ⁻²	

*The CGPM has accepted the litre (l) as an alternative name for the (dm)³ and this unit is recommended as a unit of volume for common usage.

†The CGPM has recognized kg per litre as a derived unit of density because it is of practical value.

‡When the Celsius scale of temperature is used for measurement, it is convenient to substitute degree Celsius (°C) for kelvin (K) in this derived unit, since an interval of one degree Celsius is equal to one kelvin.

Table 3. Readers are referred to the British Standards Institution publication number PD5685 (1972) for a more comprehensive list of these units.

Notes on the use of SI units

Use of multiples

In order to avoid excessively large or small numerical values in quantifying commonly used information (e.g. arterial blood pressure), the CGPM has recommended the use of multiples and submultiples of the SI units (e.g. 100 mmHg = 13.3 kPa). These factors are denoted on the prefixes and symbols shown in Table 4.

TABLE 4

Factor by which the unit is multiplied	Name of prefix	Symbol of prefix
10 ¹²	tera	T
10 ⁹	giga	G
10 ⁶	mega	M
*10 ³	kilo	k
10 ²	hecto	h
10	deca	da
10 ⁻¹	deci	d
10 ⁻²	centi	c
10 ⁻³	milli	m
10 ⁻⁶	micro	u
10 ⁻⁹	nano	n
10 ⁻¹²	pico	p
10 ⁻¹⁵	femto	f
10 ⁻¹⁸	atto	a

*In the case of the SI unit for mass, it should be noted that the prefix is appended to the gram which is not the base unit.

When using these prefixes, particular attention should be paid to the following points:

- (i) When a prefix is applied to a unit, it becomes a part of that unit to constitute a new unit which can then be subject to any applied power, e.g. 1 mm³ = 1 (10⁻³m)³ = 10⁻⁹m³ and is *not* equal to 10⁻³ (m³).
- (ii) Only one prefix should be applied to a unit at any one time, e.g. one thousandth of a millimetre is not a milli milli metre (mmm) but is a micro metre (μm).
- (iii) Errors in calculation could be avoided if quantities are expressed as powers of 10 instead of prefixes.
- (iv) The prefixes should be attached to the numerator of compound derived units whenever it is practicable.
- (v) When selecting a multiple for expressing a quantity it should be such that the numerical value lies between 0.1 and 1000, e.g. 0.000 2 m can be written as 0.2 mm; 1500 Pa = 1.5

kPa (see note on the measurement of blood pressure).

- (vi) The use of prefixes representing 10 raised to a power which is a multiple of ± 3 is recommended. The prefixes hecto (10^2), deca (10^1), deci (10^{-1}) and centi (10^{-2}) should be limited so far as possible to uses when the recommended prefixes are inconvenient.
- (vii) The decimal sign between digits is indicated by a full stop. No commas are used to divide numbers with five or more significant figures into groups of three, but instead the digits are separated by spaces into groups of three starting from the decimal sign. When there are only four figures a space is not needed. If the numerical value is less than unity a zero should precede the decimal sign, e.g. 1001; 0.000 001; 23 000.

Use of symbols denoting SI units

In the interest of consistency, the following rules should be observed in using these symbols.

- (i) The symbols should be written in roman (up-right) type regardless of the type used in the text.
- (ii) They should be unaltered in the plural.
- (iii) They have no final full stop to denote abbreviations.
- (iv) They should be written after the complete numerical value in the quantity leaving a space between the quantity and the unit. If a prefix is used there should be no space between it and the symbol, e.g. 2.54 kPa; 3.85 mm etc.
- (v) The unit symbol should be in the lower case except in those symbols which are derived from proper names, e.g. Pa, A, K, etc.
- (vi) Multiplication in a compound unit is denoted by a mid point (i.e. a 'raised full stop'), e.g. the moment of a force about a point is measured by multiplying the force by the perpendicular distance between the point and the force. Thus, $\text{moment} = \text{force} \times \text{distance}$. The SI unit of moment is the newton metre and the symbol for it is written N·m.
- (vii) When a compound unit is formed by *dividing* a unit by another, the negative index should be used except where the *divisor* is a unit of time when the solidus (/) should be used. Thus concentrations will be expressed as $\text{mol} \cdot \text{litre}^{-1}$ and blood flow will be expressed as litre/min .

Special units

There are certain units which have been retained by the CGPM because of their practical importance. Of particular interest in cardiovascular studies are the following:

Quantity	Name of unit	Unit symbol	Definition
*Time	minute hour day	min h d	
†Volume	litre	l	1 litre = 1 dm ³

*The international symbol for year is 'a' (annum) but should be written in full as 'year'.

†To avoid ambiguity between 1 and l, litre should be written in full when such ambiguity could arise.

SI units which have particular relevance to cardiovascular studies

(i) **Volume** The SI unit of volume is the cubic metre (m³) which is inordinately large for most clinical and experimental situations. Therefore, the International Committee on Weights and Measures have recommended the retention of the litre (l) which is identical to the cubic decimetre (dm³). The litre is, therefore, a special name for the cubic decimetre and will be used. For smaller volumes, the cm³ and mm³ should be used.

(ii) **Concentrations** The SI accepts two methods of expressing concentration, both of which use the litre as the unit of volume. In the case of those materials whose molecular weight is known (e.g. plasma electrolytes, urea, drugs, etc.) multiples and submultiples of the molar concentration expressed as $\text{mol} \cdot \text{litre}^{-1}$ should be used. This procedure will eliminate the usage of the equivalent concentrations which are not SI units.

In instances when the molecular weight is not known with any certainty (e.g. plasma proteins, haemoglobin, active component of vitamin B₁₂), the mass concentration should be used and expressed in terms of the litre, e.g. $\text{g} \cdot \text{litre}^{-1}$, $\text{mg} \cdot \text{litre}^{-1}$. However, in the case of haemoglobin the concentration should be expressed as $\text{g} \cdot \text{dl}^{-1}$ (where 1 dl = 100 ml).

Finally, in quantifying the formed elements of blood, it has been conventional to express the values in terms of a cubic millimetre, e.g. white blood cell count = 6000 mm⁻³. These values should be expressed in terms of a litre. The use of the litre as the unit of volume would increase the actual count by 10⁶ but would leave the significant figures unaltered. Thus a white blood cell count of 6000 mm⁻³ would be $6.0 \cdot 10^9 \text{ litre}^{-1}$ in SI units.

(iii) **Measurement of cardiac output** Although the base unit of time is the second the cardiac output should continue to be reported in terms of litre/min.

The practice of expressing cardiac output in terms of the body surface area merits a closer scrutiny. The errors involved in estimating body surface in adults have been well publicized (Krovetz, 1965). These errors are amplified in newborn infants in whom the measurement of length which is used in the calculation is notoriously difficult. Thus, cardiac output should be expressed in terms of body weight which at least has the virtue of being measured to a known accuracy.

(iv) **Pressure, peripheral resistance, and work**

To physiologists interested in the cardiovascular system the intravascular pressures are of particular importance. In themselves, they provide primary information and the derivatives of pressure such as stroke work, dP/dt max, vascular resistance, etc. provide much valuable information about the state of the myocardium and the peripheral circulation.

Pressure In the past pressures have been expressed in terms of either mmHg or cm H₂O. Derivatives of pressures such as stroke work or vascular resistance have been expressed either in arbitrary units incorporating mmHg or in terms of dynes. The SI unit for force is the newton, and accordingly the unit of pressure is the newton per square metre which is known as the pascal. The SI units for work and power are the joule and the watt, respectively. The derivations of these units are summarized in Table 3A. It is beyond the scope of this article to provide details of the relation between the conventional units of pressure and the pascal but suffice it to state that 1 mmHg = 133.332 Pa and 1 cm H₂O = 98.0665 Pa. Thus if the kilopascal (1 mmHg = 0.133 kPa) is employed as the unit of pressure, arterial systolic pressure of 130 mmHg will be equal to 17.3 kPa and a mean atrial pressure of 10 cm H₂O will be 0.98 kPa. It is felt that to avoid confusion the same multiple of the pascal, the kPa, should be retained for all intravascular pressures and also to convey the magnitude of the difference between pressure in the low and in the high pressure systems of the circulation.

Peripheral resistance It is conventional to calculate peripheral resistance from the formula:

$$\text{Resistance} = \frac{\text{Pressure difference}}{\text{Flow}}$$

The units adopted for this value are either arbitrary (peripheral resistance unit) or calculated in

dyne $\cdot$ s $\cdot$ cm⁻⁵. Before formulating yet another unit, it is necessary to consider briefly the value of resistance denoted in this way. Vascular resistance is widely used as a measure of vessel bore, and many investigators tend to use it as a means of defining changes in vessel diameter after the administration of drugs, e.g. β -adrenoreceptor antagonists.

This approach to the problem is conceptually erroneous as the relation between pressure and flow is non-linear and hence changes in calculated resistance as indicated by changes in a value derived by dividing 'pressure' by 'flow' could occur without changes in vessel diameter. However, changes in vessel diameter may be calculated, from pressure/flow curves or, by measuring changes in pressure at a constant flow. Though this discussion is an oversimplification of the problem of investigating changes in vessel bore, it is sufficient to indicate some of the difficulties which may be experienced in this field and to point to the need for the use of a single unit of measurement.

Because of these considerations it seems inappropriate for general purposes, such as the examination of changes in vessel bore, to formulate a specific unit based on SI. Instead it is recommended that peripheral resistance be expressed as follows:

$$\text{Resistance} = \frac{\text{Pressure difference (kPa)}}{\text{Flow (litre/min)}}$$

e.g. for a pressure gradient of 13.0 kPa (97.8 mmHg) and a blood flow of 5 litres/min the vascular resistance would be $13.0/5 = 2.6$ kPa $\cdot$ litre⁻¹ $\cdot$ min. When expressed in this way (i.e. with absolute values of pressure and flow presented) the readers will not be left in any doubt if a change in flow has occurred and will, therefore, be in a position to judge the validity of any interpretation placed on the calculated values of resistance. For those specialized investigations dealing with resistance as a physical phenomenon and not using it particularly as an index of vessel bore it would be acceptable to express resistance in recognized SI units. Thus the unit of resistance would be Pa $\cdot$ m⁻³ $\cdot$ s.

Stroke work Stroke work is calculated as follows: Stroke work = Stroke volume $\times$ (Mean arterial pressure - left ventricular end-diastolic pressure).

The SI unit of work is the joule (J) which is the amount of work done by a force of one newton in moving an object a distance of one metre. Thus, to express stroke work in joules it is necessary to express stroke volume in cubic metre (m³) and the arterial pressures in newton per square metre (i.e. pascal). Stroke work for a stroke volume of 70 cm³ and a mean arterial pressure of 13.0 kPa (97.8 mmHg) would be calculated as follows:

Stroke volume = $70 \text{ cm}^3 = 70 \times 10^{-6} \text{ m}^3$

Mean arterial pressure = $97.8 \text{ mmHg} = 13.0 \text{ kPa}$
 $= 13.0 \times 10^3 \text{ Pa}$

Thus stroke work = $70 \times 10^{-6} \times 13.0 \times 10^3 \text{ joule} \cdot \text{beat}^{-1}$
 $= 910 \times 10^{-3} \text{ joule} \cdot \text{beat}^{-1}$
 $= 0.910 \text{ joule} \cdot \text{beat}^{-1}$

Bicycle ergometry Bicycle ergometers are usually calibrated in kilopond metres/min (kpm/min) which are not SI units. The appropriate unit is the watt and the relation between it and the kilopond metre/min is derived as follows:

1 kpm/min = $[1 \text{ kg (i.e. force)} \times 9.8 \text{ m/s}^2 \text{ (i.e. acceleration due to gravity)}] \times [1 \text{ m (i.e. distance)}]$
 $= [9.8 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}] \times 1 \text{ m per min}$
 $= 9.8 \text{ newton} \times 1 \text{ m per min}$
 $= 9.8 \text{ joule per min}$
 $= 9.8/60 \text{ watt}$
 $= 0.163 \text{ W.}$

Thus, a value for load in a representative exercise test on a patient with heart disease would be 25 W (153 kpm/min).

(v) Viscosity

In a Newtonian liquid the coefficient of viscosity

$$= \frac{\text{Force}}{\text{Area} \times \text{Velocity gradient}}$$

The commonest unit of viscosity is the poise which is derived from the c.g.s. system.

$$\begin{aligned} 1 \text{ Poise} &= \frac{1 \text{ dyne}}{[\text{cm}]^2 \times \left[\frac{\text{cm}}{\text{s}} \times \frac{1}{\text{cm}} \right]} \\ &= \frac{1 \text{ dyne}}{\frac{\text{cm}^2}{\text{s}}} \\ &= \frac{1 \text{ dyne} \times \text{s}}{\text{cm}^2} \end{aligned}$$

In SI the units of force, area, and velocity gradient are the newton, m^2 and $\frac{1}{\text{s}}$ respectively. Thus the conversion is effected as follows:

$$\begin{aligned} 1 \text{ Poise} &= \left[\frac{1}{1000} \text{ kg} \times \frac{1}{100} \text{ m/s}^2 \right] \times \text{s} \\ &\quad \left[\frac{\text{m}^2}{10\,000} \right] \end{aligned}$$

$$= \left[\frac{1}{100\,000} \text{ kg} \cdot \text{m/s}^2 \right] \times \text{s} \left[\frac{\text{m}^2}{10\,000} \right]$$

$$= \left[\frac{1}{100\,000} \text{ N} \right] \times \text{s} = \frac{1}{100\,000} \times \frac{10\,000}{1} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$$

$$= 0.1 \text{ Pa} \cdot \text{s}$$

1 centipoise = $0.001 \text{ Pa} \cdot \text{s}$, i.e. $1 \text{ mPa} \cdot \text{s}$

Therefore the viscosity of blood would be approximately $2.55 \text{ mPa} \cdot \text{s}$.

(vi) Temperature The SI unit of temperature is the kelvin which is applicable for thermodynamic temperature and for expressing differences in temperature. However, the degree Celsius ($^{\circ}\text{C}$) which is identical to the original 1 degree centigrade has been accepted as suitable for denoting temperature for ordinary purposes. The temperature interval for a $^{\circ}\text{C}$ is the same as one kelvin. The relation between the two systems is expressed by the following. The Celsius temperature $t = T$ (thermodynamic) $- T_0$ where $T_0 = 273.15 \text{ K}$.

(vii) Blood gases and acid-base data Standard atmospheric pressure will continue to be used as an international reference. It is defined as 101.325 kPa . The conventional reference condition of standard temperature and pressure (STP) will then be 0° Celsius and 101.325 kPa .

The partial pressure of gases used for calibrating blood-gas instruments should, therefore, be denoted in kPa instead of mmHg. The CO_2 and O_2 tensions should also be expressed as such. This step may well be limited by the enthusiasm of the manufacturers to modify the scales of the instruments.

With respect to pH, there is clearly no SI unit for it. The only way in which this could be achieved is by converting the pH value to H^+ concentration and then expressing this value in terms of mole of H^+ per litre. The arguments for and against this have continued for nearly two decades and a solution does not appear to be in sight, but suffice it to add that such a step would give a spurious impression that the H^+ concentration can in fact be measured and tends to endow the measurement with an aura of precision it does not possess. The units of pH will remain the same.

The non-respiratory acid-base disturbances are usually quantified in terms of standard bicarbonate, base deficit and excess which are expressed as milli-

equivalents. In SI units the appropriate unit will be the millimole. Since the bicarbonate ion is monovalent, there will be no change in the numerical value. However, it must be remembered that standard bicarbonate itself is conceptually incorrect when used to analyse acid-base disturbance *in vivo* and could lead to inaccurate diagnoses. The authors recommend that the use of the terms standard bicarbonate, base deficit and excess be discontinued (Stoker *et al.* (1975) for references). Such a change is, at the moment, arguable and, therefore, would not be mandatory in articles in this journal.

The aspects of SI which are of particular interest to those engaged in cardiovascular studies have been reviewed in this article, bearing in mind the necessity for formulating a concise and consistent editorial policy regarding units. As a consequence, much of the element of choice permitted by the CGPM regarding abbreviations and symbols has been eliminated from these recommendations. The reader is, however, referred to two other documents listed in the references for more detailed information.

References

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Appendix 1

Definitions of the SI base-units

Metre

The metre is the length equal to 1 650 763.73 wave lengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.

Kilogram

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

Second

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium -133 atom.

Ampere

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

Kelvin

The kelvin, unit of thermodynamic temperature, is the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water.

Candela

The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.

Mole

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

Appendix 2

Commonly used terms in cardiovascular studies

Force	newton (N)
Flow	litre/min
Blood flow through specific organ	litre/min $\cdot$ kg ⁻¹ tissue
Cardiac output	litre/min $\cdot$ kg ⁻¹
Heart rate	beats/min
Oxygen consumption	cm ³ /min or litre/min
Potential difference	volt (V)
Power	watt (W)
Pressure	kilopascal (kPa)
Partial pressure of gases	kPa
Rate of change of pressure	dP/dt (kPa/s). The maximum rate of change of pressure should be denoted by dP/dt max
Resistance—vascular (see text)	kPa $\cdot$ litre ⁻¹ $\cdot$ min
Temperature	degree Celsius ($^{\circ}$ C)
Time	second (s)
	minute (min)
	hour (h)
	day (d)
Viscosity	pascal second (Pa $\cdot$ s)
Volume	litre (to be written in full except when used with a prefix)
Work	joule (J)

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