Commentaries

The International System of Units (SI) in Historical Perspective

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Abstract: American medical journals are shifting to selected SI (Système International d'Unités) units for reporting measurements. Limitation of SI units deemed suitable for use in reporting clinical laboratory results stems from recommendations put forth by the International Federation of Clinical Chemistry and the International Union of Pure and Applied Chemistry. Limitations are: 1) the liter as sole recommended unit of volume in concentration measurement; 2) substance concentration (unit mole) favored over mass concentration (submultiples of the kilogram); and 3) discouraging the use of the prefixes hecto-, deca-, deci-, and centi-.

Further discussion by the American Medical Association and other organizations is required before consensus in the US medical community can be reached as to extent of and time frame for conversion to SI for reporting clinical laboratory measurements. (*Am J Public Health* 1987; 77:1400–1403.)

Introduction

American medical journals are shifting to the use of le Système International d'Unités (SI) for reporting measurements.[1,2] Judging by title and content of some editorial comments, however, there is confusion as to what is really meant by "a shift to SI." The January 1987 issue of the *Annals of Internal Medicine* contained an editorial titled "The American shift to medical SI units" and used terms such as "older conventional metric units" and "non-SI metric units."[2] This implies that there are special units within the SI for medicine and that medicine is currently using metric units that are not part of SI. This paper will discuss the development of SI and recommendations developed within the scientific community for implementation of certain SI units in reporting clinical laboratory measurement results.

What is SI?

SI is no more than an extension of the centimeter/gram/second (CGS) system proposed in 1873, the meter/kilogram/second (MKS) system proposed in 1901, and the meter/kilogram/second/ampere (MKSA) system proposed in 1950. SI was adopted by more than 50 countries at the 11th Conférence Général des Poids et Mesures (CGPM) in 1960. SI consists of three classes of units: base, derived, and supplementary.

SI Base Units

Until 1971, SI consisted of six base units (Table 1). In 1966, the Commission on Clinical Chemistry of the International Union of Pure and Applied Chemistry (CCC-IUPAC), the International Standards Organization (ISO), and the International Union of Pure and Applied Physics (IUPAP) proposed a seventh base unit to recognize the molecular constitution of substances, because many physical quantities of different substances bear significant relationships to each other when compared for equal numbers of molecules (or whatever the appropriate constituent entity may be, such as atoms or ions). This seventh base unit, the mole, was adopted in 1971 by the 14th CGPM (Table 1).

SI Derived Units

Derived units are formed from base units according to algebraic relations (multiplication and division) linking corresponding quantities. Examples of derived units commonly encountered in clinical laboratory and medical journals are given in Table 2. For certain derived units, special names and symbols have been accepted (Table 2).

SI Supplementary Units

There are two supplementary units, the radian for plane angle and the steradian for solid angle. The CGPM has declined to state whether these are base or derived units, although the Conférence International des Poids et Mesures (CIPM) considered these to be dimensionless derived quantities.

Multiples and Submultiples of Units

In practical use, excessively large or small numerical values may occur with SI units. The required number can be simplified by the use of special prefixes to the unit symbol (Table 3). Multiples and submultiples of the unit of mass (kilogram), however, are constructed by attaching the appropriate prefix to the word gram or the symbol g.

In products or quotients of units, each of the units may carry a prefix. It is, however, recommended to combine the prefixes into one symbol in a quotient, if possible in the numerator. The prefix forms one entity with the following unit. Thus, for example, 1 mm^2 signifies one millimeter squared (0.000 001 m^2) and not one milli square meter (0.001 m^2).

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Glossary of Abbreviations Used

CCC-IUPAC:	Commission on Clinical Chemistry of the International Union of Pure and Applied Chemistry
CGPM:	Conférence Général des Poids et Mesures (General Conference of Weights and Measures)
CGS:	centimeter/gram/second
CIPM:	Conférence International des Poids et Mesures
ICSH:	International Committee for Standardization in Haematology
IFCC:	International Federation of Clinical Chemistry
ISO:	International Standards Organization
IUPAP:	International Union of Pure and Applied Physics
MKS:	meter/kilogram/second
MKSA:	meter/kilogram/second/ampere
SI:	système international d'unités
WAPS:	World Association of (Anatomic and Clinical) Pathology Societies

TABLE 1—Names, Symbols, and Definitions of SI Base Units

Physical Quantity	Unit Name	Unit Symbol	Definition
Length	meter	m	"Equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom." (11th CGPM, 1960).
Mass	kilogram	kg	"Equal to the mass of the international prototype of the kilogram" (3rd CGPM, 1901)
Time	second	s	"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 cesium-133 atom." (13th CGPM, 1967).
Electric Current	ampere	A	"That constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length." (CGPM, 1948).
Thermodynamic Temperature	Kelvin	K	"The fraction of 1/273.16 of the temperature of the triple point of water." (13th CGPM, 1967). The 13th CGPM also decided that the unit kelvin and its symbol K should be used to express an interval or a difference of temperature. In addition to the thermodynamic temperature (symbol T), expressed in kelvin, use is also made of Celsius temperature (symbol t) defined by the equation: $t = T - T_0$, where T_0 = 273.15 K by definition. The Celsius temperature is expressed in degrees Celsius (symbol °C). The unit "degree Celsius" is thus equal to the unit "kelvin" and an interval or a difference of Celsius temperature may also be expressed in degrees Celsius.
Luminous Intensity	candela	cd	"The luminous intensity, in the perpendicular direction, of a substance of 1/600 000 square meter of a black body at the temperature of freezing platinum under a pressure of 101 325 newton per square meter." (13th CGPM, 1967)
Amount of Substance	mole	mol	"The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12." When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. (14th CGPM, 1971).

Although the spelling in official ISO Recommendations is always metre and kilogramme, the simpler US spelling has been chosen.

Retention of Widely Used Non-SI Units

The CGPM recognized that certain units are not part of SI but are important and widely used (Table 4). The liter, widely used in commerce as well as in scientific investigation, was redefined by the 12th CGPM to equal exactly 1 dm^3 ($10^{-3}m^3$). It is recommended that the name not be employed to give results of high-accuracy volume measurement or high-accuracy concentration measurement.[3]

Using SI Units

Any measurement in science, medicine, or technology can be adequately and unambiguously expressed with SI; with a few exceptions, no basic change in the units used in the clinical laboratory, for example, is mandated. Analyte concentration can be expressed with SI as, e.g., mg/mL or mg/dL, because SI does not stipulate that all concentration measurements must use the liter as unit of volume, nor is it obligatory with SI to report all analyte concentrations as substance concentration (i.e., mol/L).

Recommendations for Selected SI Units to be Used in Medicine

Implementation of SI in expressing results of clinical laboratory measurements has long been a major concern of IUPAC and IFCC. As early as 1960, the Danish Society for Clinical Chemistry and Clinical Physiology developed a proposal that was presented to CCC-IUPAC. After thorough review of comments and discussions, CCC-IUPAC and the

TABLE 2—Names, Special Names, and Symbols of Some SI Derived Units

Physical Quantity	Unit Name	Unit Symbol	Physical Quantity	Unit Name	Unit Symbol	Expression in Terms of Other Units	Expression in Terms of SI Base Units
Area	square meter	m^2	Frequency	hertz	Hz		s^{-1}
Volume	cubic meter	m^3	Force	newton	N		$m \cdot kg \cdot s^{-2}$
Mass Concentration	kilogram per cubic meter	$kg \cdot m^{-3}$	Pressure, stress	pascal	Pa	$N \cdot m^{-2}$	$m^{-1} \cdot kg \cdot s^{-2}$
Substance Concentration	mole per cubic meter	$mol \cdot m^{-3}$	Energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
Mass Fraction	kilogram per kilogram*	$kg \cdot kg^{-1}$	Power, radiant flux	watt	W	$j \cdot s^{-1}$	$m^2 \cdot kg \cdot s^{-3}$
Substance Fraction	mole per mole*	$mol \cdot mol^{-1}$	Luminous flux	lumen	lm		$cd \cdot sr$†
Volume Fraction	cubic meter per cubic meter	$m^3 \cdot m^{-3}$	Illuminance	lux	lx		$m^{-2} \cdot cd \cdot sr$†

*These kinds of quantities are dimensionless, and the coherent unit is unity. The units kg/kg, mol/mol, and m^3/m^3 are permissible alternatives.
†In this expression the steradian (sr) is treated as a base unit.

TABLE 3—SI Prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{-1}	deci	d	10	deka	da
10^{-2}	centi	c	10^2	hecto	h
10^{-3}	milli	m	10^3	kilo	k
10^{-6}	micro	μ	10^6	mega	M
10^{-9}	nano	n	10^9	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a	10^{18}	exa	E

TABLE 4—Units in Use with the SI

Quantity	Name	Symbol	Value in SI unit
time	minute	min	1 min = 60 s
time	hour	h	1 h = 60 min = 3 600 s
time	day	d	1 d = 24 hr = 86 400 s
plane angle	degree	°	$1° = (\pi/180)$ rad
plane angle	minute	′	$1' = (1/60)° = (\pi/10\ 800)$ rad
plane angle	second	″	$1'' = (1/60)' = (\pi/648\ 000)$ rad
volume	liter	L*	1 L = 1 dm^3 = $10^{-3}m^3$
mass	ton (metric)	t	1 t = 10^3 kg
area	hectare	ha	1 ha = 1 hm^2 = 10^4 m^2

*The United States has accepted the symbol L for liter.

Council of IFCC approved the publication of Quantities and Units in Clinical Chemistry: Recommendation 1966.[4] These recommendations included:

- only the liter should be used as denominator in concentration units involving the volume of a mixture;
- the mole is proposed as seventh base unit and amount of substance, unit mole, should be used whenever possible in reporting clinical laboratory results; and
- factors that are powers of 10 with exponents that are whole multiples of 3 should be preferentially used.

These concepts were adopted by the International Committee for Standardization in Haematology (ICSH), the International Federation of Clinical Chemistry (IFCC), and the World Association of (Anatomic and Clinical) Pathology Societies (WAPS) who, after extensive discussions, issued a common declaration in 1972.[5] The ICSH, however, recommended at that time that hemoglobin concentration continue to be reported as mass concentration (g/L or g/dL).[5]

The principal reason given by the chemistry community for advocating certain rules and limitations when SI is used to report results is that the introduction of SI in the clinical laboratory offers the scientific and medical community an opportunity to further standardize test methods and units for reporting laboratory results, an opportunity that may not occur again.

Consequences of Recommended Limitations

The Liter as Sole Unit of Volume in Concentration Measurements

The consequences of using only the liter as the unit of volume in concentration measurements (mass, number, or substance), rather than the deciliter or other submultiples, is probably no more than a slight irritation. Laboratory values now reported per dL will increase by a factor 10: e.g., 15.0 g/dL hemoglobin becomes 150 g/L. It will, however, prevent laboratories from circumventing the use of powers of 10 in reporting, for example, cell count results, should they so wish. For example, a red cell count of 5.25×10^{12}/L could, without the "liter rule," also be reported as $5.25/10^{-12}$L, equivalent to 5.25/pL, a perfectly acceptable application of SI.

Exponents of 10 That are Whole Multiples of 3

Discouraging the use of exponents of 10 other than whole multiples of 3, i.e., hecto, deca, deci, and centi (Table 3) may cause more problems. For example, the length of a 6-foot person would need to be given as either 1.83 m or 1829 mm and not as 182.9 cm; the length of a newborn would be either 0.49 m or 490 mm, not 49 cm. In the laboratory, molar absorptivities, now generally stated as $mmol^{-1}.L.cm^{-1}$, would need to be specified as $mmol^{-1}.L.(10\ mm)^{-1}$.

Amount of Substance Favored Over Mass Amount

The exclusive use of amount of substance, unit mole, when an elementary entity can be defined for a given component could, when blindly followed, lead to confusion and possibly errors. The elementary entity of normal human hemoglobin can be defined in two ways: the tetramer consisting of 4 heme groups and a globin moiety of 4 α chains and 4 β chains, or as the monomer consisting of 1 heme group and a globin moiety of 1 α and 1 β chain. A hemoglobin concentration of 15.0 g/dL (150 g/L) would, reported as substance concentration, be 2.33 mmol/L or 9.31 mmol/L, depending on whether the tetramer or the monomer is considered the elementary entity. There are, however, excellent publications that contain extensive tables relating "conventional" values (most already in units that are part of SI) to comparable values in units as recommended by the chemistry community,[2,6–8]

Medical journals plan, in shifting to SI, to add SI units in parentheses after "conventional" units in 1987, to add "conventional" units after SI units in 1988, and after 1988 require SI units only.[1] In the ICSH reference method for hemoglobinometry,[9] the recommended reagent contains, per liter, 200 mg $K_3Fe(CN)_6$, 50 mg KCN, 140 mg KH_2PO_4, and 0.5–1.0 mL of nonionic detergent. In 1988, according to journal requirements, this composition would be specified as 0.607 mmol (200 mg), 0.768 mmol (50 mg), 1.029 mmol (140 mg), and 1.5–1.0 mL; after 1988 as 0.607 mmol, 0.768 mmol, 1.029 mmol, and 0.5–1.0 ml. One could speculate on how much additional time the average laboratory technician will need after 1988 to make up this reagent accurately.

Included in the shift to SI are clinical laboratory results of drug concentration in therapeutic drug monitoring and emergency toxicology. At the same time there is increasing pressure to have drugs prescribed in molar doses. The reaction to this proposal is one of virtually total opposition.[10] Certainly, in this area, relevance to clinical practice and safety of patients must be the primary considerations.

Conclusion

Although a number of major medical journals have initiated a shift to the use of a selected set of SI units, there is as yet no consensus within the medical community on a conversion plan for implementation of SI. A Steering Committee on SI Unit Conversion of the American Medical Association has been established to make recommendations on the extent and time frame of conversion. It is to be expected that further discussion will be required before consensus can be reached throughout the medical community.

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ERRATA

In: Stanbury M, Rosenman KD: A methodology for identifying workers exposed to asbestos since 1940. Am J Public Health 1987; 77:854–855. On page 855, column 1, a portion of the first sentence was left out. We apologize for the gross omission. The text should read as follows (material underlined is the part that was omitted): "In the late 1970s, the National Cancer Institute did a nationwide asbestos notification program that targeted all US physicians and Social Security recipients with letters containing information about asbestos, and targeted major shipbuilding cities with a mass media campaign."

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In: Cereseto S, Waitzkin H: Economic development, political-economic system, and the physical quality of life. Am J Public Health 1986; 76:661–666. The following two typographical errors were not caught in the proofreading, for which the authors have expressed their regret to the readers of the Journal: In Table 3, in the regression of life expectancy, the standardized beta coefficient for political economic system should be 0.33, mpt −0.33; in the regression of calorie supply, the standardized beta coefficient for political economic system should be 0.35, not −0.35.

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IPPNW Invites Original Research Studies for 1988 World Congress

The International Phyicians for the Prevention of Nuclear War (IPPNW) announces its second annual call for abstracts on original research related to the prevention of nuclear war. The next presentation will be held during the Eighth IPPNW World Congress in Montreal, Canada June 2–6, 1988.

Only substantive, completed research studies are invited. Reports of works in progress or editorials will not be selected. Because the prevention of nuclear war is a long-term goal, the emphasis should be on scientific methodology. Those whose papers are accepted for presentation will receive a stipend of US $500.

Those wishing to present 15 minute papers should submit abstracts of 250 words by January 1, 1988 to: IPPNW, 126 Rogers Street, Cambridge, MA 02142, USA, Attn: Susan Fox.