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● ***Forum***

THE ADVANTAGES AND SIMPLIFICATIONS OF SI UNITS IN HEALTH PHYSICS*

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SI STANDS for Système Internationale d'Unités (International System of units) which has replaced the mksa (meter–kilogram–second–ampere) system (NBS 1986; NCRP 1985). Almost every country on earth, including the People's Republic of China, has adopted SI and is putting it into use. The United States of America is noteworthy in its resistance to the use of SI; readers outside the U.S. may be amused or dismayed by the fact that we even need an opinion such as this in our journal.

SI units are divided into three classes: the seven base units (meter, m; kilogram, kg; second, s; ampere, A; kelvin, K; mole, mol; candela, cd), the derived units and the supplementary units. Examples of derived units with special names include hertz, Hz (s^{-1}); newton, N (kg m s^{-2}); pascal, Pa (N m^{-2}); joule, J (N m); watt, W (J s^{-1}); coulomb, C (A s); and volt, V (J C^{-1}).

There are several derived units with special names admitted for purposes of safeguarding human health. For activity, there is the becquerel (1 Bq ≡ 1 s^{-1}; therefore, 1 Ci = 3.7×10^{10} Bq). Note that you may use s^{-1} for anything, but Hz is limited to use for frequency or nonstochastic variations in time, and Bq is only for activity whose temporal nature is stochastic. The gray (unit symbol, Gy; 1 Gy = 1 J kg^{-1}) is for absorbed dose, D; specific energy imparted, z; kerma, K; and absorbed dose index, D_I. The sievert (unit symbol, Sv) is the unit of dose equivalent, H, and of dose equivalent index, H_I. The National Bureau of Standards and the International Commission on Radiation Units and Measurements define dose equivalent as $H = \sum_i Q_i D_i$, where Q_i and D_i are the quality factor and absorbed dose of the ith kind of ionizing radiation. It is important to divorce any discussion of SI concerning *units* from discussions of radiation protection *quantities*, such as dose equivalent, that continue to have problems (Ruby 1985; Greening 1986; Dunster 1986; Murnaghan 1986).

There are also derived units expressed by means of special names, such as radiation chemical yield, $G(x)$, measured in mol J^{-1} or some suitable submultiple. G is the number of moles of chemical species x changed, created or destroyed per unit ionizing energy deposited. Another derived unit with a special name is exposure, X, expressed in C kg^{-1}. The old roentgen is defined in terms of SI base units as 1 R ≡ 2.58×10^{-4} C kg^{-1}, exactly.

WHY SWITCH TO SI?

In my opinion, we must change to SI *now*. We make the change not so much for ourselves but for our children and grandchildren. There are three compelling reasons to switch: 1) SI enhances communication by providing international standardization, 2) SI is coherent and thus simplifies calculation, and 3) SI dramatically facilitates the teaching of health physics.

A common, coherent language facilitates communication between cultures in an ever smaller world. Just as English has become a standard in scientific communication, so will SI. The need for a common set of units was clearly illustrated during and after the Chernobyl disaster; members of the press repeatedly criticized our profession for using two different unit systems. For international health physics, SI is inevitable.

"A major advantage of the SI is its coherence. A system is coherent when no conversion factors other than unity are needed for the formation of units derived from the base and supplementary units" (NCRP 1985). In a coherent system of units, you can be sure that if all quantities in a formula are entered in that system, the answer will be in that system of units. There is no need for "incoherent" conversion factors (such as 3.7×10^{10}). Avoidance of the conversion factors associated with units such as the roentgen and curie simplifies calculations and minimizes calculational errors.

Finally, experience with SI units in teaching health physics shows that the physics becomes much less obscure when simple units are used. The less advanced the audience, the more important such simplification becomes. I have found that understanding what is being measured

* Use of SI units is advocated by most scientists and is required in manuscripts published in *Health Physics*. The SI metric system utilizes prefixes rather than E-notation as recommended by the author of this paper. *Editor*

the authors of *The physics of radiology*, 4th edition, on their almost complete integration of SI units into their text (Johns and Cunningham 1983). Authors in the field of health physics have been less successful, with roots firmly in the old units, making conversions without insight (such as cGy for rad).

Look for advantages when you feel besieged by apparent drawbacks. Just when you've decided that the becquerel is too small a unit to conveniently express the release of ^{131}I from the Chernobyl reactor ($\approx$300 PBq, or 300 E15 Bq), think of how good it is for environmental monitoring. (Maximum ^{131}I air concentrations in Finland were about 2 Bq m^{-3}.)

Finally, although this is little comfort to many, think about the consequences of *not* converting to SI. We'll become further out of step with the rest of the world; our children will think we're crazy or lazy or both; and we'll spend time, money, and creative energy dealing with archaic units when a better system is already here. For those who still aren't convinced of the importance of standardization, I challenge you to read Nesmith's lighthearted but poignant review of historical clashes over standards and the expense and folly of not having them (Nesmith 1985).

EXAMPLES OF SI SIMPLIFICATIONS

Exposure. In SI units, exposure, X, is measured in C kg^{-1}. Exposure rate, $\dot{X}$, is stated in terms of C kg^{-1} s^{-1} by the ICRU and the NBS (ICRU 1980; NBS 1986), but it is much easier to understand *physically* in terms of SI base units, namely, A kg^{-1}. What is an ion chamber except an ammeter or a coulombmeter connected to a mass of air? This physics is easy to understand for the student, without the needless introduction of the roentgen. For example,

$$\begin{aligned} 100 \text{ mR y}^{-1} &= 100 \times 10^{-3} \times 2.58 \\ &\quad \times 10^{-4} \text{ C kg}^{-1} \div (3.156 \times 10^{7} \text{ s y}^{-1}) \\ &= 8.18 \times 10^{-13} \text{ C kg}^{-1} \text{ s}^{-1} \\ &\simeq 10^{-12} \text{ A kg}^{-1} \\ &= 1 \text{ pA kg}^{-1}; \end{aligned}$$

or

$$10\ \mu\text{R h}^{-1} = 0.72 \text{ pA kg}^{-1}.$$

Another example of obscuring physics by using the roentgen occurs when ion chambers are calibrated. Typically, when one sends an ion chamber out for calibration, a value of so-and-so many nanocoulombs per roentgen (nC R^{-1}) is returned by the calibration laboratory for certain conditions of calibration, such as ^{60}Co radiation at standard temperature and pressure (STP). By analyzing the units, one realizes that nC R^{-1} has the dimensions of *mass*: 1 nC R^{-1} = 10^{-9} C $\div$ 2.58 $\times$ 10^{-4} C kg^{-1} = 3.88 $\times$ 10^{-6} kg, or 3.88 mg. The calibration laboratory is really determining the effective mass of air in your chamber under those conditions. This is the mass that should be used to calculate the dose to a medium in the Bragg–Gray formula.

Since exposure and exposure rate are becoming less and less acceptable in health physics, and are used very little in medical physics, some argument can be made for eliminating the concept of exposure altogether. Note that it does not appear in the Bragg–Gray formula; only the mass of gas in the chamber and the charge Q need be measured.

We are all aware that the calibration of instruments always comes down to adjusting a screw somewhere or coming up with a "fudge factor" to make things come out right. Even though we've tried to make them, there is no instrument on earth that truly reads out in dose equivalent (or dose equivalent index) units. So we settle for something that satisfies the regulators. For ion chamber instruments, some attempt is made to make them read correctly in exposure rate units over a limited energy range, and the better models do this quite well. But the scale could be calibrated just as easily in μGy h^{-1} for ^{60}Co as in mR h^{-1}. The same physics is going on, the same energy dependence applies, and the same uncertainties and systematic errors are present *regardless* of what the units on the scale are called. The Bragg–Gray theory tells us that a chamber can be made to read just as well for absorbed dose as for exposure, given the conditions of calibration. To those who argue that "we should stick close to what is being measured" (a principle with which I agree), I can only point out that exposure rate measuring devices are not calibrated ammeters and balances for measurement of air mass. They are all calibrated against known radiation sources, not against ammeters and balances.

Working Level (WL) and Working Level Month (WLM). These are two of the worst units I have ever encountered. Historically, the WL was a concentration of 100 pCi of ^{222}Rn in 1 L of air in equilibrium with its short-lived radioactive progeny. But expressed as joules per cubic meter of potential alpha-energy concentration (PAEC), the physics becomes clearer. What could be simpler than an annual limit on intake of 0.02 J? SI values of derived air concentrations, annual limits on intake and annual limits on exposure have been published by the ICRP (1981).

Activation of a target. Consider the activation of a target, $A(n, \gamma)B$, in which there are so few interactions that the number of target atoms can be assumed not to diminish during irradiation. The saturation activity that can be induced in a target activated under these conditions is

$$A_{\text{sat}} = \varphi \sigma N_0,$$

where φ is the fluence rate of projectiles (m^{-2} s^{-1}), σ is the activation cross section per atom of A (m^2), and N_0 is the number of target atoms.

As expected for a coherent system of units, A_{sat} is automatically in Bq if all other quantities are in SI base units.

CONCLUSION

Vigorous efforts to switch to SI units as soon as possible will result in enhanced communication, both at home and abroad, through the standardization of scientific expression. Calculations become simpler in SI because noncoherent conversion factors disappear. Finally, using SI units simplifies teaching the concepts of physics, as illustrated by the examples above.

Once a decision to switch has been made, use of SI is facilitated by strategies such as avoidance of conversions, use of SI prefixes and "E-notation," elimination of archaic units and the use of SI references and texts. Professional health physicists now being trained are conversant in SI units; unfortunately for them, they have to begin work in a world that is burdened with archaic, incoherent units.

Let's get on with it!

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Internal dosimetry. The cumulated activity, U, is merely the total number of nuclear transitions that have occurred in the organism and is expressed in Bq s. Note that 1 Bq s = 1(transition s^{-1})(s) = 1 transition; i.e., it is dimensionless.

$$U(t) = \int_0^t q(\tau)d\tau = q_0 \int_0^t R_e(\tau)d\tau,$$

where $q(\tau)$ is the activity as a function of time, q_0 is the activity at time = 0, and $R_e(\tau)$ is the effective retention function. Cumulated activity is important because the absorbed dose is directly proportional to it. U must be multiplied by the average energy per transition and fraction of that energy that is absorbed in a mass and divided by the mass to obtain the absorbed dose.

The absorbed dose rate to water from a weak β-emitter such as ^3H is directly proportional to concentration because all of the energy is (essentially) absorbed where it is emitted. Thus, the *absorbed dose rate* is

$$\dot{D}(\text{Gy s}^{-1}) = CE_\beta,$$

where C is the concentration, Bq kg^{-1}, and E_β is the average energy of the β-particles in joules.

The use of coherent SI units for internal dosimetry also avoids such monstrous units as "gram rads per microcurie hour" (Loevinger and Berman 1976).

How many atoms in a becquerel? Given $A = \lambda N$, with A in Bq, λ in s^{-1}, and N dimensionless, for $A = 1$ Bq, N is numerically the same as the *average life in seconds*. This illustrates the inverse relationship between specific activity and half life.

STUMBLING BLOCKS ON THE PATH TO SI

There are two kinds of stumbling blocks on the path to SI: problems inherent in the SI units themselves (some of which are common to *any* unit system) and problems of our current environment that can be remedied.

All unit systems have some arbitrary starting points. Two of these in SI result in non-unity values for the coulomb (actually, the ampere-second) and the mole. SI defines the ampere as that amount of electric current that produces a force of 2×10^{-7} newtons per meter of conductor between parallel conductors one meter apart. In addition, SI has chosen the constants ϵ_0 and μ_0 such that $\epsilon_0\mu_0 = c^{-2}$, where c is the speed of light (Kowalski 1986). These choices result in the value of the elementary charge of $1.60217733 \times 10^{-19}$ coulombs (CODATA 1986). This number is also the number of joules per electron volt. As long as there are particle acceleration machines with voltage controls (e.g., diagnostic x-ray machines), we will continue to have quantum energies expressed in this noncoherent, quasi-SI unit called the electron volt. Reducing the number of energy units to only two is great progress when compared to the days of foot pounds, Rydbergs, calories, Calories, British Thermal Units, barrels of oil, tons of TNT and cords of wood (Hayden 1981).

Table 1. Common absorbed dose rate units and their equivalent in SI units.

	Gy s^{-1}	
1 rad s^{-1}	= 0.01	= 10 mGy s^{-1}
1 rad min^{-1}	= 1.67×10^{-4}	= 167 μGy s^{-1}
1 rad h^{-1}	= 2.78	= 2.78 μGy s^{-1}
1 rad d^{-1}	= 1.16×10^{-7}	= 116 nGy s^{-1}
1 rad y^{-1}	= 3.17×10^{-10}	=.317 pGy s^{-1}
1 mrad h^{-1}	= 2.78×10^{-9}	= 2.78 nGy s^{-1}
1 mrad d^{-1}	= 1.16×10^{-10}	= 116 pGy s^{-1}
1 mrad y^{-1}	= 3.17×10^{-13}	= 317 fGy s^{-1}

The other arbitrary and bothersome quantity in SI that remains is the mole, the unit of amount of substance. Historically, scientists wanted the ratio of atomic mass to mass number to be about unity when atomic mass was expressed in grams per mole. Today's definition is "the number of atoms in 0.012 kg of ^{12}C," resulting in the Avogadro constant being 6.0221367×10^{23} mol^{-1} (CODATA 1986). Consequently, there is one noncoherent element about data currently in use with SI: all periodic tables and charts of the nuclides I have seen give atomic and particle masses in g mol^{-1} [the so-called (unified) atomic mass unit, $1.6605402 \times 10^{-27}$ kg (CODATA 1986)] rather than in kg mol^{-1}. A truly SI periodic table would give atomic masses such as 0.2380289 for U, rather than 238.0289. One must divide atomic masses found on current periodic tables by 1000 to benefit from coherence. Many students have fallen victim to this hidden factor on a test.

Whatever system of units is chosen, time continues to be a quantity that must be converted from one unit to another. The number of days in a year is determined by celestial mechanics beyond the reach of standard-setting organizations. The noncoherent factors of 60, 60 and 24 that relate seconds, minutes, hours and days are not likely to change, either, regardless of the unit system being used.

Unfortunately, at least eight different absorbed dose rate units commonly occur in the health physics and radiation biology literature, as shown in Table 1. Any comparison of results from one paper to another requires conversion from one set to another. Use of SI prefixes allows the expression of absorbed dose rates as numbers between 1 and 1000, as shown in Table 1.

The main stumbling block to a simple transition to SI is the fact that most existing data and texts are published in old units. Ah, what I would give for a *Radiological Health Handbook* completely in SI! (Publishers, are you listening?) This means energies in fJ in addition to eV, keV and MeV. The curie (once the activity of 1 gram of Ra) and the roentgen (1 esu cm^{-3} of dry air at STP) are historical accidents that have now become a burden. So who will sell us the *Table of Isotopes* or ICRP Report No. 38 in SI?

can be greatly enhanced by the use of SI units in place of the traditional ones. My favorite examples of obscurity forced on us by the old units are the "nanocoulomb per roentgen" and the annual limit on intake (ALI) for Rn progeny. Before reading the discussion that follows, can you explain what a nC R^{-1} is or what fundamental concept is used to express the ALI for Rn progeny?

STRATEGIES FOR COPING WITH SI

I suggest several strategies for coping with SI units: 1) avoid converting to the old units; 2) learn and exploit the SI prefixes; 3) use "E-notation," 4) absolutely avoid archaic units when SI units will do, 5) use text and reference books that are uniformly in SI, and 6) look for advantages when you feel besieged by apparent drawbacks.

Don't convert—make a clean break. You will never learn a new system of units by continually converting to the old any more than you can ever really learn another language by continually translating it into your native language. You must learn to "think" in the other language. For those who have lived outside the USA, experience has shown that to learn Celsius temperatures, you simply must use them without conversion. You get up on a crisp autumn morning, look at the thermometer, go outside and say, "Aha! So this is what 8°C feels like!" Then, and only then, do you know Celsius temperatures, not by converting them to Farenheit. The same holds true for foreign currency, distances in kilometers, European cooking recipes and SI units.

Learn and use the SI prefixes. SI has formalized a system of prefixes to denote powers of ten (see Roessler 1984). The SI prefixes greatly simplify the use of the system, but they are of no use unless they are in your head, not in a reference book. Thus, I urge you to memorize all of them from atto to exa, and use them to avoid cumbersome powers-of-ten notation. Objections to SI units, such as "The becquerel is too small," or "The gray is too big," are only made by people who are not conversant in SI prefixes. Don't combine prefixes, such as mμm (the old millimicron, now the nanometer). Pronunciations of unit prefixes should also be standardized. The accent is correctly placed on the first syllable for kilo and micro. Thus, kilometer is pronounced "KILL oh me ter," with the "kilo" pronounced just like in kilogram; and micrometer is pronounced "MY crow me ter," just like microgram. Note that "my CROM eh ter" is a machinist's tool for very precise measurement of distances.

Contrary to popular usage, the prefix "giga" is correctly pronounced "JIH ga," with a soft "g," as in "gigantic" (from the same Greek root), rather than with a hard "g," as in "giggle."

Use "E-notation." Powers of ten have traditionally been expressed as, for example, 3.1556×10^7. The computer language FORTRAN, in use since the 1950s, has a so-called "exponential format," or E-format, that would express the number as +0.31556E+08. Due to the tyranny of the computer printout, such notation has become fairly standard (although with the "mantissa" as a number between 1 and ten and leading zeroes in exponents suppressed) so that the number becomes 3.1556 E7. Thus, the uppercase "E" has come to be shorthand for "times 10 to the," and our number can be read conveniently as "three point one five five six E 7." This also has the advantage of being exactly the buttons you push on your calculator when entering numbers. Reading E7 as "E seven" or E − 4 as "E minus 4" facilitates easy and accurate computation. The use of E-notation also simplifies the conversion into and out of SI prefixes in calculations. (Please note that such powers should not be read as "E to the 7" or "E to the minus 4" since that means $e^7 = (2.71828\ldots)^7$ not 10^7, or $e^{-4} = 2.71828\ldots^{-4}$, not 10^{-4}.)

Another benefit of the E-notation is the avoidance of superscripts so that in tables, extraneous characters are eliminated, and the readability of photocopies enhanced. The computer printout and the calculator have thus conspired to make these subtle changes in our language and speech; changes for the better and simpler.

Use of the solidus or "slash" (/) is discouraged in some style publications (American Institute of Physics 1978) because of the problem of knowing how much of the following text is to be included in the denominator. Multiple slashes, such as dis/min/gram, are expressly forbidden by NBS and NCRP due to the same ambiguity (NBS 1986; NCRP 1985). The use of the solidus to permit the plotting of dimensionless numbers has been seen for years in ICRU publications, but its use in this context is both unnecessary and confusing since it obscures meaning and results in multiple slashes in several ICRU publications. I specifically oppose the ICRU notation, such as described in NCRP Report No. 82, p. 31 (NCRP 1985) and recommend that of the AIP in its place. The AIP would suggest an axis label for a graph of "Absorbed Dose, D (Gy)," with the quantity, symbol, and unit symbol all given. Such notation enhances communication.

Never use archaic units or notation. The use of obsolete units is strongly discouraged. The popular biological shorthand for the microliter, μL, used to be "lambda"; this should be avoided. The angstrom, Å (10^{-10} m), should never be used. The old "fermi" was conviently defined as 10^{-15} m, or 1 fm, so that its symbol has not changed. The barn, 10^{-28} m^2, quaint and picturesque though it may be, does not fit in SI. Nor does the "micron"; this is correctly called the micrometer, μm. And shocking as it may sound, the "degree" was banished from "kelvin" in 1967 since "degree" has many meanings and contributes nothing to meaning when preceding absolute temperature. Thus, it is now correct to speak of "a few kelvins" or "a few millikelvins." Note that the degree is still correct with the Fahrenheit and Celsius temperature scales.

Use reference books in SI units. Unfortunately, there are few such books available yet. With the exception of ICRP, ICRU and some UNSCEAR publications, few books have appeared exclusively in SI units. I commend