AAPM REPORT NO. 57

RECOMMENDED NOMENCLATURE FOR PHYSICAL QUANTITIES IN MEDICAL APPLICATIONS OF LIGHT

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Report of Task Group 2
AAPM General Medical Physics Committee

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I. INTRODUCTION

The growing number of medical applications of lasers and other optical technology has brought together scientists from diverse backgrounds. Communication in the field has suffered from inconsistency in terminology, units, and symbols. The purpose of this report is to recommend standard nomenclature for quantities frequently used, especially in dosimetry and modeling of radiation transport.

We have examined a number of reports from other bodies including: 1) International Commission on Radiation Units and Measurements Report 33-Radiation Quantities and Units, 2) International Union of Pure and Applied Chemistry-Glossary of Terms Used in Photochemistry, 3) Quantities and Units of Light and Related Electromagnetic Radiation. Int. Standard IS0 31/6, International Organization for Standardization 1980, 4) Radiometric and Photometric Characteristics of Materials and their Measurement. International Commission on Illumination (CIE) 1977 No. 38, and 5) American National Standard Nomenclature and Definitions for Illuminating Engineering ANSI 27.1-1967.

As well, earlier drafts of this document have been circulated among our European and North American colleagues. Fortunately, it is possible to derive a consensus on definitions for the physical quantities of interest. Not surprisingly, however, there is still considerable disparity among the symbols which arise from the radiation physics, chemistry, radiation transport, and engineering literature. Therefore, while we recommend the universal symbols summarized in Table I, we recognize that conventions in the different disciplines will probably cause some remaining diversity in usage.

The report is organized in three sections: quantities describing the radiation field. quantities describing interaction of the radiation field with tissue, and quantities recommended for dosimetry records.

II. QUANTITIES DESCRIBING THE RADIATION FIELD

Radiant energy *(Q):* Total energy emitted, transferred or received as electromagnetic radiation. The SI unit is J.

Radiant energy flux (F): The quotient of dQ by dt, where dQ is the increment of radiant energy in time interval dt. This quantity is identical to the radiant power (see below) and the SI unit is W. While the symbol Φ is preferred and is common in the physics literature, its use should be avoided where confusion with quantum yield may arise.

Radiant power (P): Power emitted, transferred or received as electromagnetic radiation. The SI unit is W.

Table I - List of physical quantities, symbols, and units

Quantity	Symbol	SI Unit
Radiant energy	Q	J
Radiant energy flux	Φ	W
Radiant power	P	W
(Energy) fluence	H_o	J m^{-2}
(Energy) fluence rate	E_o	W m^{-2}
(Energy) Radiance	L	W m^{-2} sr^{-1}
Irradiance	E	W m^{-2}
Radiant exposure	H	J m^{-2}
Radiant intensity	I	W sr^{-1}
Index of refraction	n	
Absorption coefficient	μ_a	m^{-1}
Scattering coefficient	μ_s	m^{-1}
Total attenuation coefficient	μ_t	m^{-1}
Phase function	$p(\hat{\Omega}, \hat{\Omega}')$	
Average cosine of scattering angle	g	
Mean free path		m
(Single scattering) albedo	a	
Optical depth	τ	
Effective attenuation coefficient	μ_{eff}	m^{-1}
Penetration depth	δ	m
Transport scattering coefficient	μ_s'	m^{-1}
Transport coefficient	μ_t'	m^{-1}
Transport (single scattering) albedo	a'	
Reflectance	R, r	
Transmittance	T	

(Energy) fluence ***(H_o):*** Total radiant energy incident on an infinitesimal sphere containing the point of interest, divided by the cross-sectional area of that sphere. The SI unit is Jm^{-2}.

(Energy) fluence rate ***(E_o):*** Ratio of total radiant power incident on an infinitesimal sphere containing the point of interest to the cross-sectional area of that sphere. The SI unit is Wm^{-2}. This term is preferable to the equivalent "space irradiance."

(Energy) radiance *(L):* Radiant energy transported at a given field point in a given direction per unit time per unit solid angle per unit area perpendicular to the propagation direction. The SI unit is W $m^{-1} sr^{-1}$.

Irradiance *(E):* Radiant power incident on an infinitesimal *surface* element containing the point of interest divided by the area of that element. The SI unit is W m^{-1}. Other terms such as power density, flux density, and intensity which have been used to describe this quantity should be avoided.

Radiant exposure *(H):* Radiant energy incident on an infinitesimal *surface* element containing the point of interest divided by the area of that element. The SI unit is J m^{-2}. The term energy density should be avoided.

Radiant intensity *(I):* Radiant power per unit solid angle. The SI unit is W sr^{-1}.

Explanatory Notes:

1. Confusion often arises between the quantities irradiance and fluence rate or, equivalently, exposure and fluence. Irradiance applies to a particular surface whereas fluence rate can be defined for free space. The distinction can be made mathematically by considering the radiance L (Ω) which is a function of direction Ω and a surface element defined by the normal vector $\hat{\mathbf{n}}$. We have

$$E_o = \int L(\hat{\Omega})\, d\hat{\Omega}$$

$$E = \int L(\hat{\Omega})\, \hat{\Omega} \cdot \mathbf{n}\, d\hat{\Omega}$$

Clearly, if the incident radiation is a collimated, perpendicularly incident beam, then

$$E_0 = E$$

2. The radiation field can also be specified in terms of photon number instead of radiant energy. The field descriptors then become photon fluence, etc. The IUPAC recommends that the subscript *"p"* be used to denote these symbols-for instance E_{op}. This seems unnecessarily cumbersome as it should be clear from the context and units whether the number of photons is being referred to.

3. The quantities defined above may also be defined as spectral densities and denoted by the subscript " λ ". For example the spectral fluence E_{ol} is the fluence per unit wavelength at the wavelength λ and is defined by $E_{ol} = \delta E_0 / \delta \lambda$.

III. QUANTITIES DESCRIBING THE INTERACTION OF THE RADIATION FIELD WITH TISSUE

Index of refraction *(n)*: The ratio of the speed of light in vacuum to the speed of light in the medium. Of course tissue is not homogeneous so this can only be defined in the sense of a volume average.

Absorption coefficient (μ_a): The probability that a photon will be absorbed on traversing an infinitesimal distance in tissue *(dx)*, divided by that distance. In other words, the probability of absorption is $\mu_a dx$.

Scattering coefficient (μ_s): The probability that a photon will be scattered on traversing an infinitesimal distance in tissue *(dx)*, divided by that distance. The probability of scattering is, therefore, $\mu_s dx$.

Total attenuation coefficient (μ_t): Sum of the absorption and scattering coefficients. The SI unit is m^{-1}.

Phase function $p(\hat{\Omega}, \hat{\Omega}')$: Probability density function describing the angular dependence of scattering. Given that a photon moving in direction $\hat{\Omega}$ is scattered, the probability that it will then be propagating in $d\hat{\Omega}'$ about $\hat{\Omega}'$ is $p(\hat{\Omega}, \hat{\Omega}')\, d\hat{\Omega}'$.

Average cosine of scattering angle *(g)*: $g = \int_{4\pi} p(\hat{\Omega}, \hat{\Omega}')(\hat{\Omega} \cdot \hat{\Omega}')\, d\hat{\Omega}'$. It is usually assumed that tissue is an isotropic medium so that p $(\hat{\Omega}, \hat{\Omega}')$ depends only on $(\hat{\Omega} \cdot \hat{\Omega}')$ and g is therefore independent of initial angle.

Mean free path: Mean distance between photon interactions $(1 / \mu_t)$. The SI unit is m.

Single scattering albedo *(a)*: Ratio of the scattering coefficient to the total attenuation coefficient, $a = \mu_s / \mu_t$.

Optical depth (t): The physical depth, *d*, expressed in units of mean free paths, $\tau = \mu_t d$.

Effective attenuation coefficient (μ_{eff}): Under many irradiation conditions the fluence rate will decrease exponentially with distance from the source, $H_0 \propto \exp(-\mu_{eff}\, r)$, where μ_{eff} is defined as the effective attenuation coefficient. This coefficient is independent of the irradiation condition if measurements are performed at sufficient distance from the source, so that μ_{eff} is a function only of μ_a, μ_s, $p(\hat{\Omega}, \hat{\Omega}')$. The SI unit is m^{-1}.

Penetration depth (d): The reciprocal of the effective attenuation coefficient. Again, this will be independent of irradiation conditions only under the circumstances described above. Sometimes the term penetration depth is reported as the depth in tissue at which the fluence rate divided by the incident fluence rate equals e^{-1}. This usage is not recommended, as the fluence rate may not be an exponential function of depth near the surface. The SI unit is m.

Transport scattering coefficient *(μ_s'):* The transport or reduced scattering coefficient is given by $\mu_s' = (1-g)\,\mu_s$ and is an effective isotropic scattering coefficient arising from the diffusion approximation. The SI unit is m^{-1}.

Transport coefficient *(μ_t'):* The transport coefficient or reduced attenuation coefficient is $\mu_t' = (1-g)\,\mu_s + \mu_a$. The SI unit is m^{-1}.

Transport single scattering albedo *(a'):* The transport or reduced albedo is the ratio of the transport scattering coefficient to the transport coefficient $a' = \mu_s' / \mu_t'$. The SI unit is m^{-1}.

Reflectance *(R, r):* The reflectance of a surface or medium is the fraction of incident flux which is reflected. It is often useful to differentiate light reflected from the surface of the tissue from that reflected by the bulk medium. It is recommended that the symbol *“r”* be used for surface reflectance and *“R”* for bulk reflectance. Subscripts may also be added for clarity from the following list:

sp	specular	refers to light directionally reflected from a surface at an angle of reflection equal to the angle of incidence.
d	diffuse	refers to light reflected from within a medium due to scattering. Can also be used to refer to the reflection of diffuse (as opposed to collimated) radiation from a surface.
t	total	the sum of diffuse and specular reflection.
i	internal	the reflection of flux incident on a surface from within the medium back into the medium.
e	external	the reflection d flux incident on the surface of a medium back into the external environment.

For example, the fraction of diffuse flux incident on the surface from within the medium and internally reflected is denoted by r_{id}.

Transmittance (T): The fraction of incident flux which is transmitted through the tissue. As above, subscripts can be added for clarity from the following:

t	total
p	primary (unscattered)
d	diffuse

IV. QUANTITIES RECOMMENDED FOR DOSIMETRY RECORDS

The fundamental parameters which govern the rate and total amount of energy absorbed at a specific location in tissue are the energy fluence rate and energy fluence, respectively. For example, the rate of local energy absorption is $\mu_a H_0$. While this quantity can be calculated given enough information, its direct measurement is difficult at best. It is more common to specify the irradiation conditions, as recommended below.

Surface irradiation: The irradiance and exposure should be recorded. If there is significant spatial variation in these parameters within the beam, this should also be measured and recorded.

Interstitial irradiation: For a “point” source such as a cut end optical fiber, the power and energy emitted by the fiber should be recorded. This should be measured in water as measurements in air may be prone to artifacts caused by refractive index mismatch. For a distributed line source the power and energy emitted per unit fiber length in water should be recorded.

Spectral information: Many applications use “monochromatic” light, and it is sufficient to record the wavelength as long as the bandwidth is less than one nanometer. For multi-line lasers (e.g., argon) the wavelength and relative power of each line should be recorded. For wideband sources, such as arc lamps, the relative power should ideally be measured as a function of wavelength over the entire range of significant contribution. The wavelength resolution required in such a measurement depends on the detailed nature of the spectrum and the medical application.