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Metrological basis for in situ Measurements

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International system of quantities
ISO & IEC 80000

Metrology

Science of measurement and its application. Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.

Quantity

Property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference. A quantity intended to be measured is called **measurand**.

Measurement

Process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.

Measurement unit

Real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number.

Measurement uncertainty

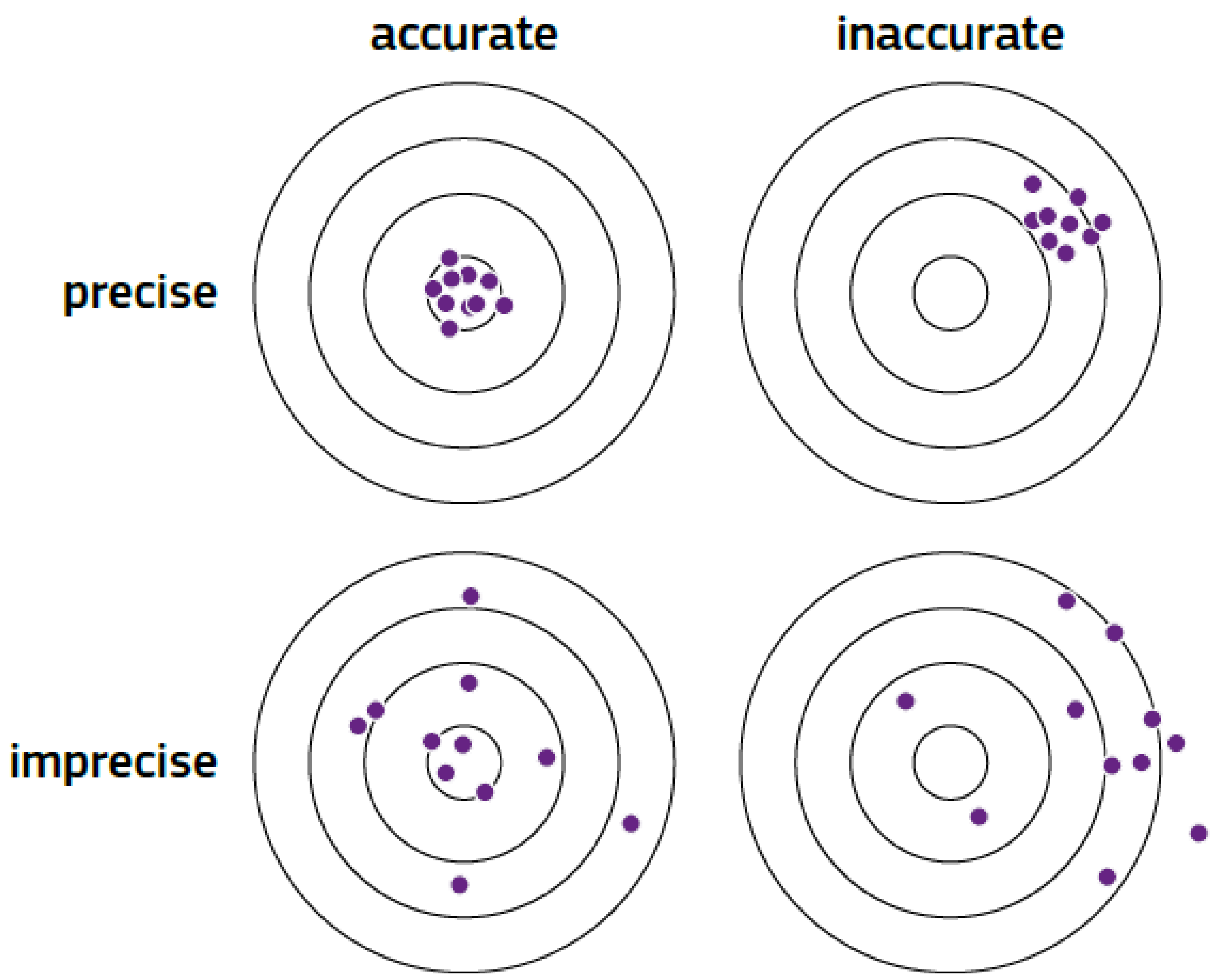
Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Repeatiblity, Reproducibility, Precision, Accuracy…

Definitions

Repeatability: same method, same lab, same person, same conditions (ideally).

Reproducibility: different methods, different labs, different conditions.



Calibration and response of instrument

Calibration: Operation that, under specified conditions, in a first step establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

The calibration factor, N, is defined for reference conditions as the conventional true value of the quantity, Q, divided by the reading of the instrument (corrected if necessary), M:

$$N = Q / M$$

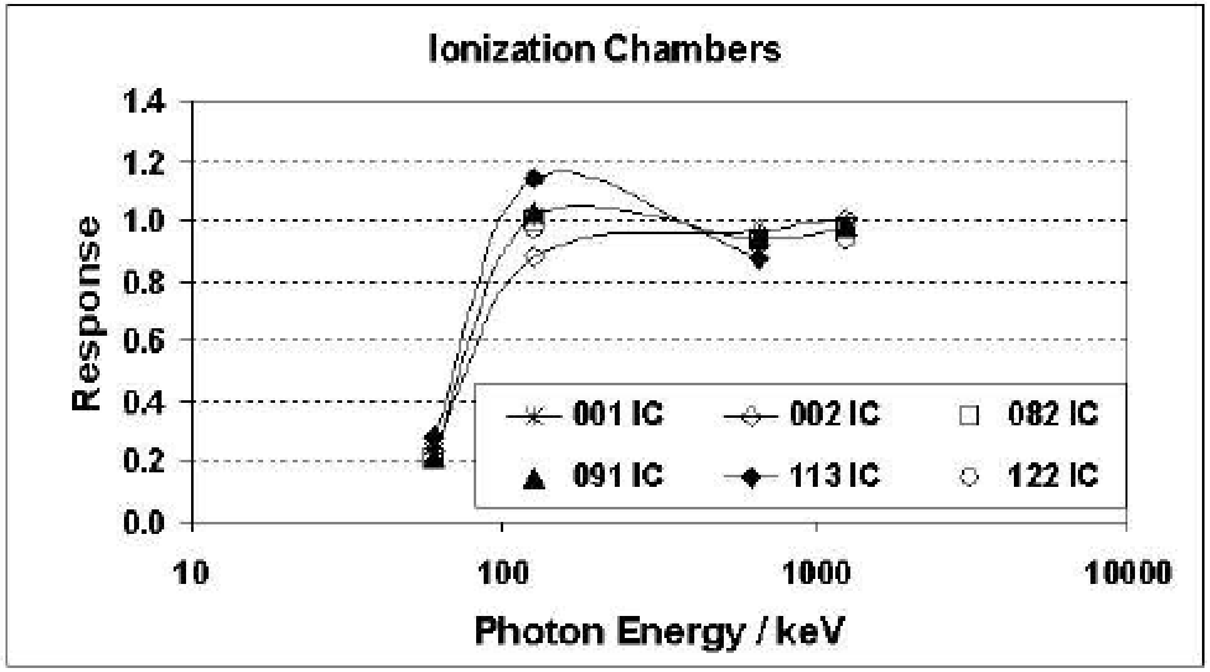
Response of the instrument, R_Q: Is the reading of the instrument, M, divided by the conventional true value of the quantity, Q, causing it:

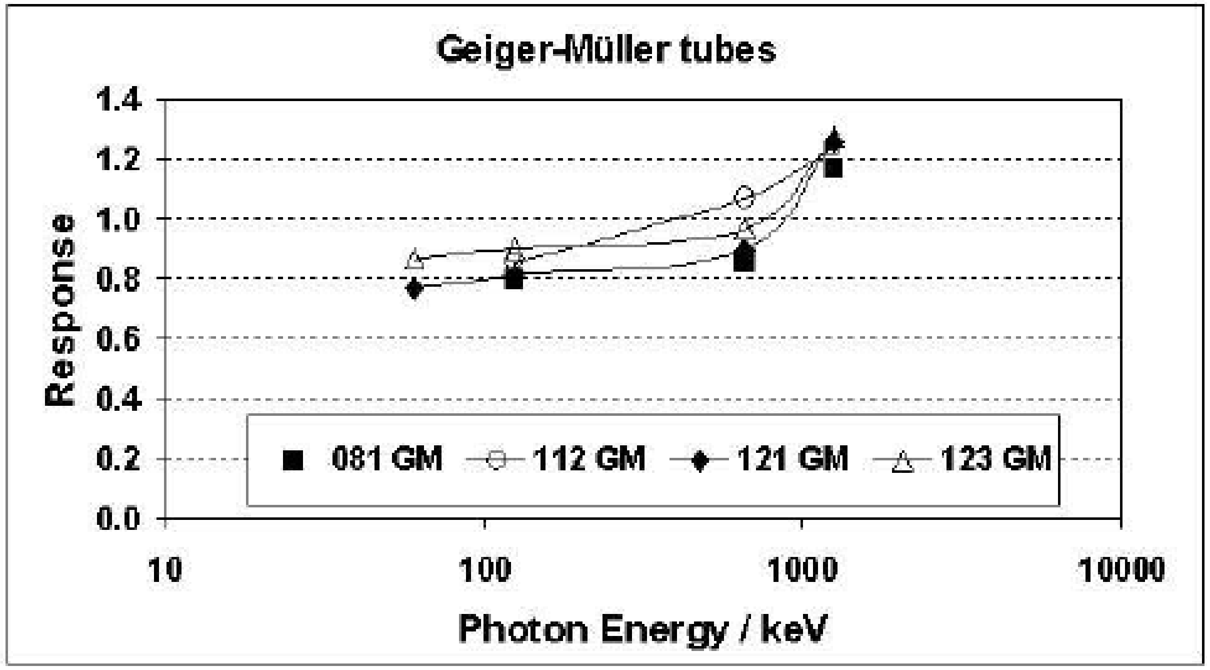
$$R_Q = M / Q$$

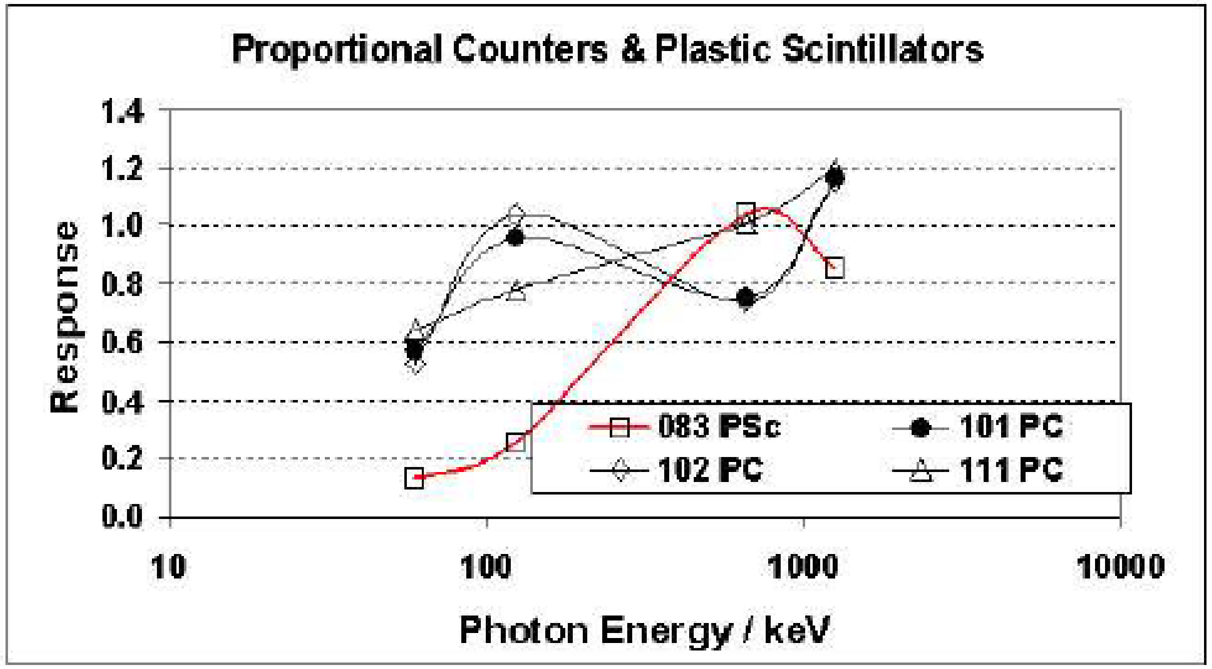
The response may vary when changing the experimental conditions due to linearity, angular or energy influences, among others. $R_Q = 1/N$ when the reference conditions are procured.

Response and calibration factors can be dimensionless when the instrument indicates readings in terms of the quantity. Response and calibration factors can be dimensionless when the instrument indicates readings in terms of the quantity.

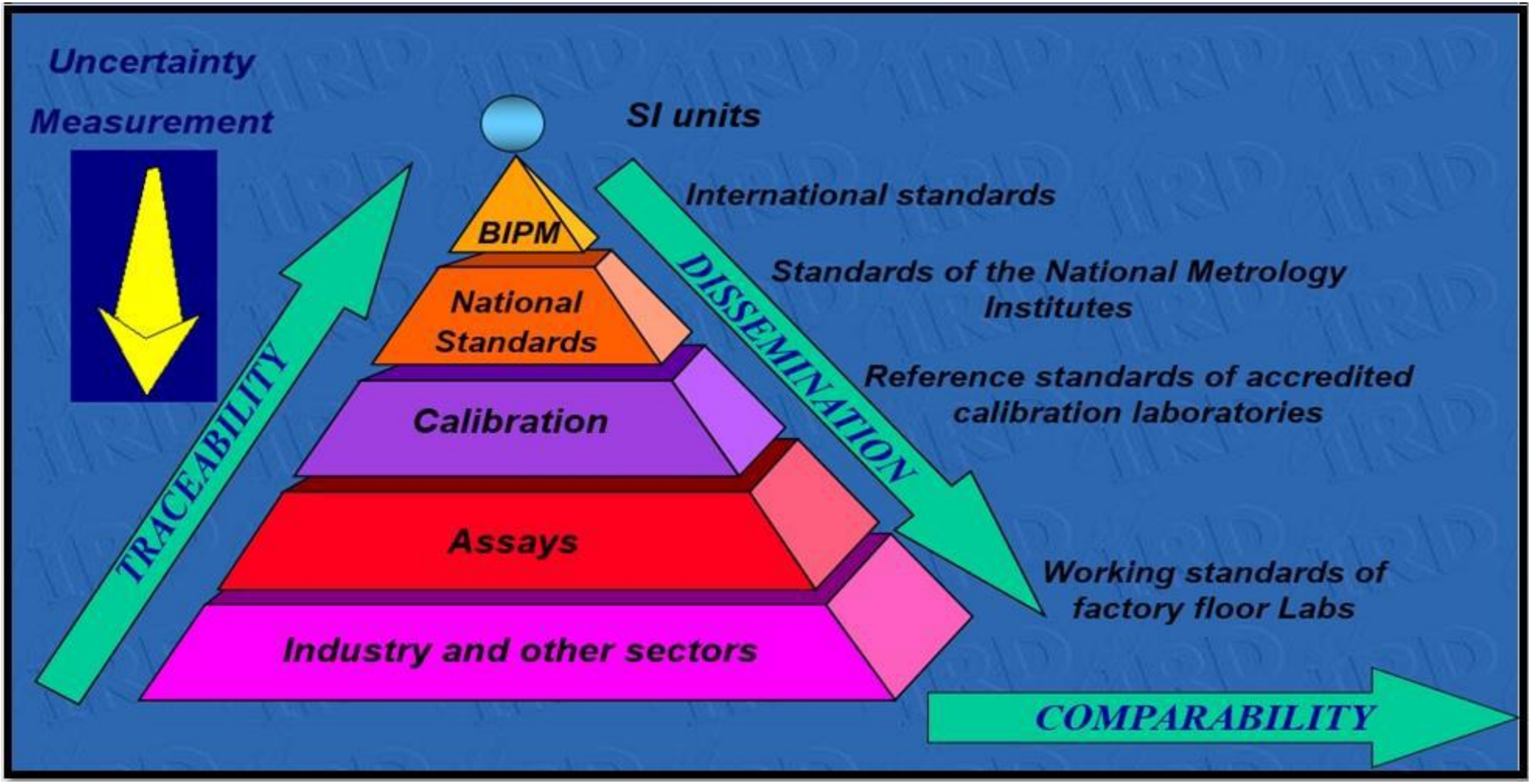
Calibration and response of instrument







Metrology hierarchy



da Cruza P. A. L.. Et al, 2018

Radiation protection quantities

Primary Standards

Physical quantities
Fluence, Φ
Kerma, K
Absorbed dose, D

***Conversion factors* (ICRP-74, ICRU-57, ISO 4037-3)**

Computational

ICRU-39 & 51

Operational Quantities
Ambient dose equivalent, $H^*(d)$
Directional dose equivalent, $H'(d,\Omega)$
Personal dose equivalent, $Hp(d)$

ICRP-103

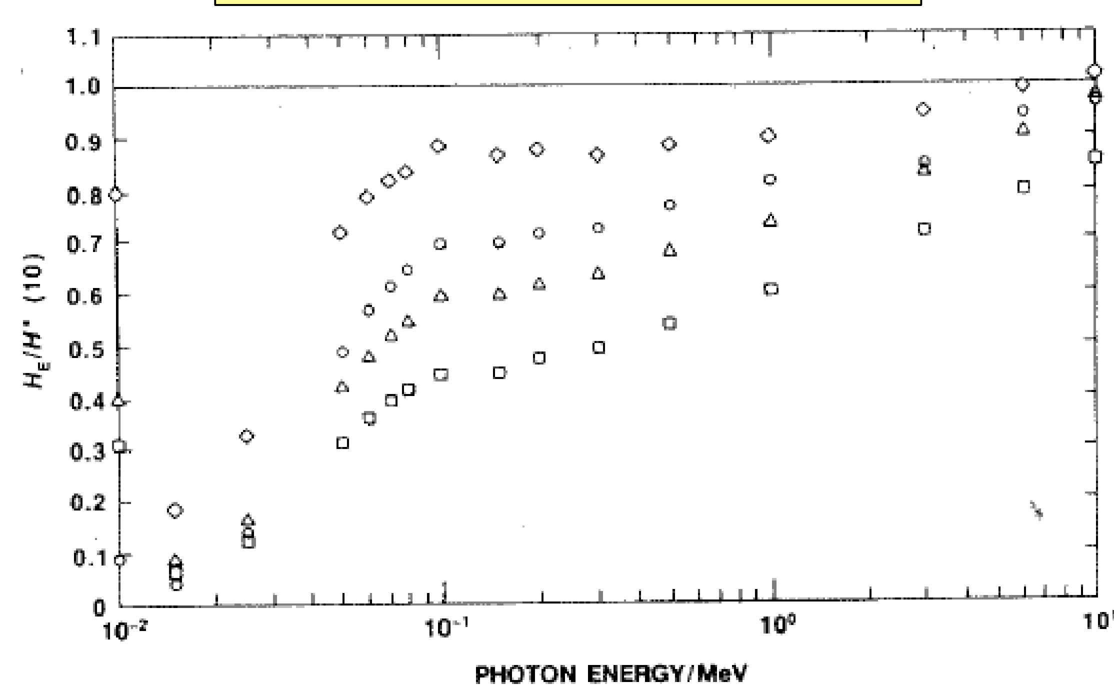
Protection quantities
Organ absorbed dose, D_T
Organ equivalent dose, H_T
Effective dose, E

Comparison & Estimation

Calibration, Type testing

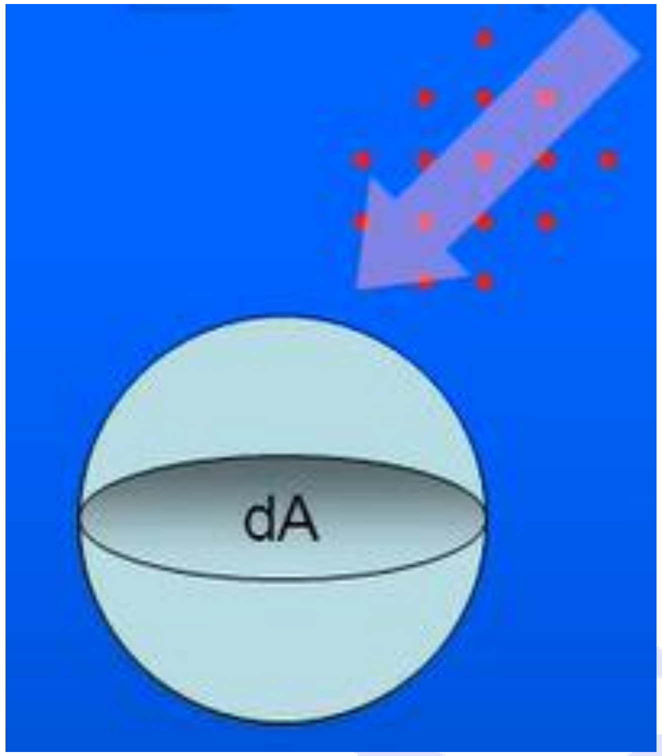
Experimental measurements
Readout
Instrument response
Corrections

H*(10) is a conservative estimate of E



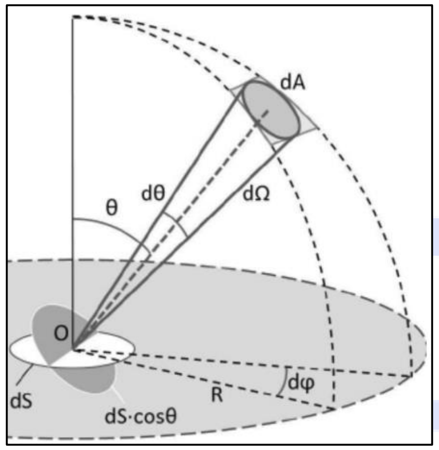
Scalar radiometric quantities

Definition	Units
The ***particle number, N***, is the number of particles that are emitted, transferred, or received	1
The ***radiant energy, R***, is the energy (excluding rest energy) of the particles that are emitted, transferred, or received. For particles with energy between E and E+dE: $R_E = E \cdot N_E$	J
The **fluence**, Φ, is the quotient of d*N* by d*a*, where d*N* is the number of particles incident on a sphere of cross-sectional d*a*: $\Phi = dN/da$	m^{-2}
The **energy fluence**, Ψ, is the quotient of d*R* by d*a*, where d*R* is the radiant energy incident on a sphere of cross-sectional d*a*: $\Psi = dR/da$	$J\ m^{-2}$



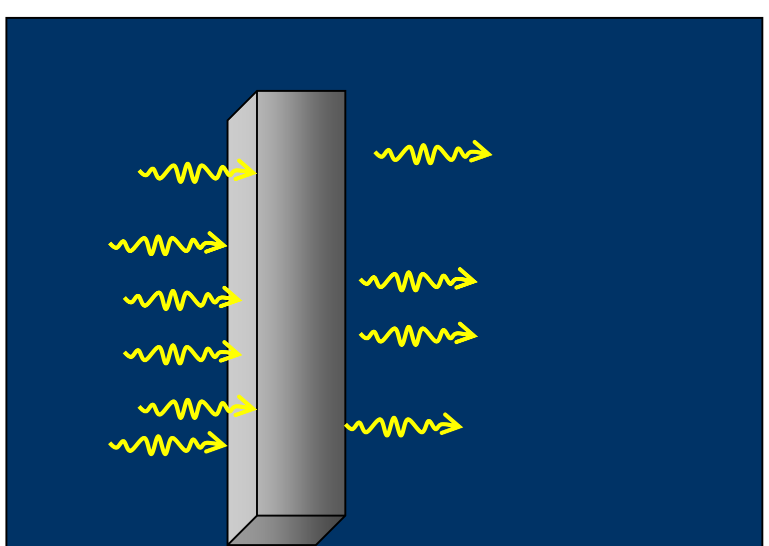
Scalar radiometric quantities

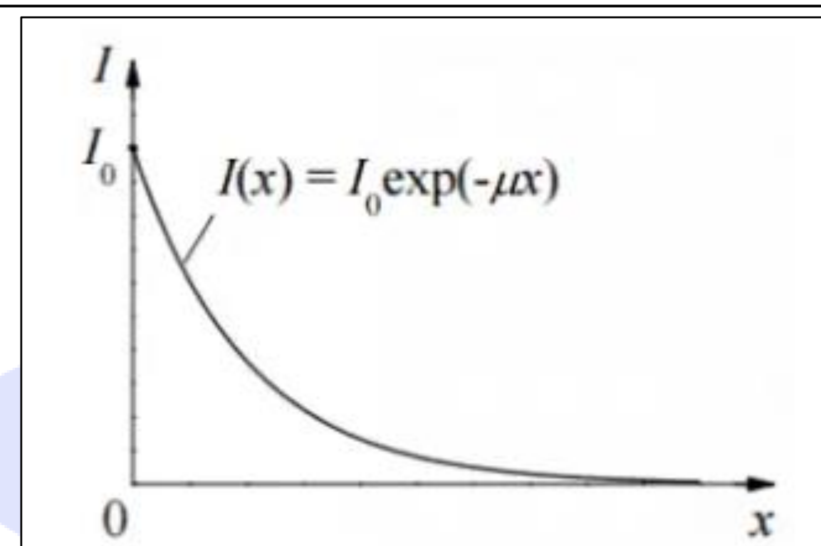
Definition	Units
The **flux,** $\dot{N}$, is the quotient of d*N* by d*t*, where d*N* is the increment of the number of particles in the time interval d*t*: $\dot{N} = \mathrm{d}N/\mathrm{d}t$	s^{-1}
The **energy flux,** $\dot{R}$, is the quotient of d*R* by d*t*, where d*N* is the increment of radiant energy in the time interval d*t*: $\dot{R} = \mathrm{d}R/\mathrm{d}t$	W (= 1 J s^{-1})
The **fluence rate,** $\dot{\Phi}$, is the quotient of d*Φ* by d*t*, where d*N* is the increment of the fluence in the time interval d*t*: $\dot{\Phi} = \mathrm{d}\Phi/\mathrm{d}t$	m^{-2} s^{-1}
The **energy fluence rate,** $\dot{\Psi}$, is the quotient of d*Ψ* by d*t*, where d*Ψ* is the increment of the energy fluence in the time interval d*t*: $\dot{\Psi} = \mathrm{d}\Psi/\mathrm{d}t$	W m^{-2}
The **particle radiance,** $\dot{\Phi}_\Omega$, is the quotient of d$\dot{\Phi}$ by d*Ω*, where d$\dot{\Phi}$ is the fluence rate of particles propagating within a solid angle d*Ω* around a specified direction: $\dot{\Phi}_\Omega = \mathrm{d}\dot{\Phi}/\mathrm{d}\Omega$	m^{-2} s^{-1} sr^{-1}
The **energy particle radiance,** $\dot{\Psi}_\Omega$, is the quotient of d$\dot{\Psi}$ by d*Ω*, where d$\dot{\Psi}$ is the energy fluence rate of particles propagating within a solid angle d*Ω* around a specified direction: $\dot{\Phi}_\Omega = \mathrm{d}\dot{\Phi}/\mathrm{d}\Omega$	W m^{-2} sr^{-1}



Interaction Coefficients

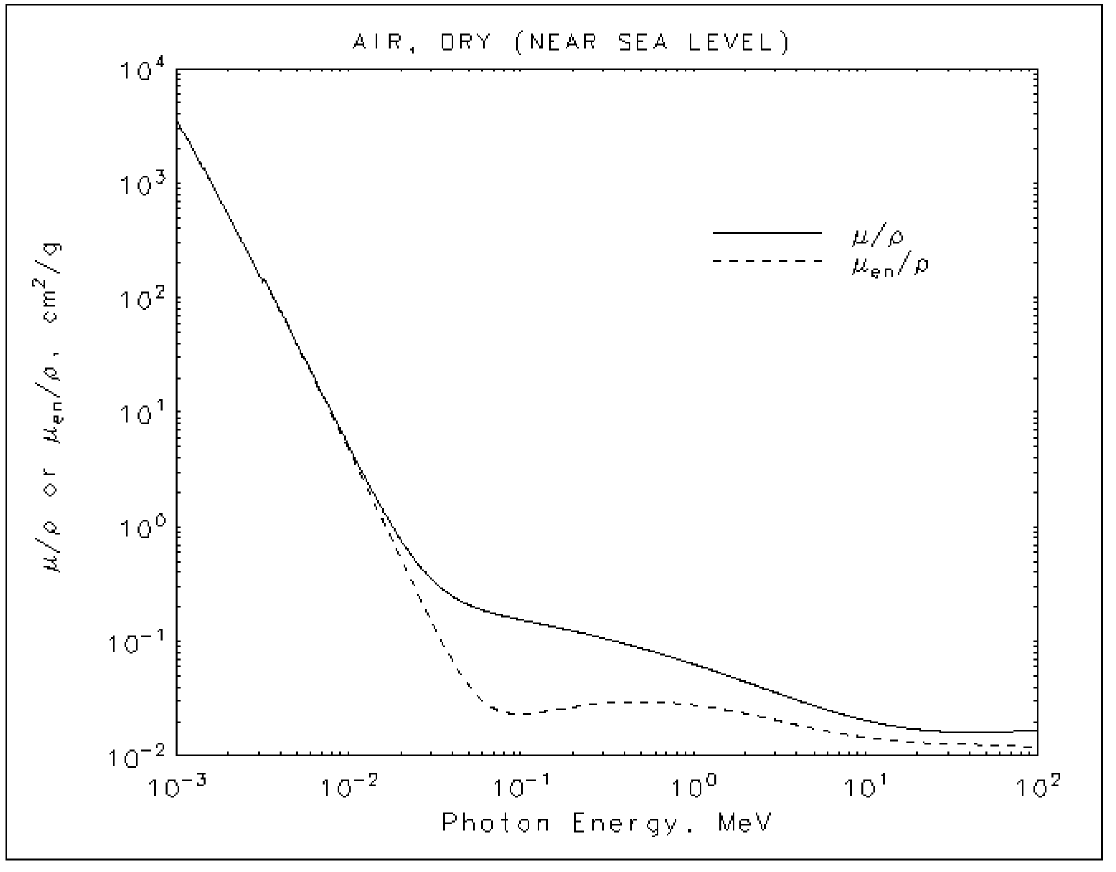
Definition	Units
The **linear attenuation coefficient, μ,** of a given material yields the probability that at normal incidence an uncharged particle undergoes an interaction in a material layer of thickness d*l* is μ d*l*	m^{-1}
The **mass attenuation coefficient, μ/ρ**, of a material, for uncharged particles of a given type and energy, is the quotient of d*N*/*N* by *ρ* d*l*, where d*N*/*N* is the mean fraction of the particles that experience interactions in traversing a distance d*l* in the material of density ρ: $$\frac{\mu}{\rho} = \frac{1}{\rho \cdot dl}\frac{dN}{N}$$	$m^2\ kg^{-1}$
The **mass energy-transfer coefficient, μ_{tr}/ρr**, of a material, for uncharged particles of a given type and energy, is the quotient of dR_{tr}/*R* by *ρ dl*, where dR_{tr} is the mean energy that is transferred to kinetic energy of charged particles by interactions of the uncharged particles of incident radiant energy *R* in traversing a distance dl in the material of density *ρ*: $$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho \cdot dl}\frac{dR_{tr}}{R}$$	$m^2\ kg^{-1}$
The **mass energy-absorption coefficient, μ_{en}/ρ**, of the material for uncharged particles is defined as: $$\frac{\mu_{en}}{\rho} = \frac{\mu_{tr}}{\rho}(1 - \mathrm{g})$$ Where ***g*** is the fraction of kinetik energy transferred to charged particles and subsequently lost on average in radiative processes (bremsstrahlung, in-flight anhilitation and fluorescence radiations).	$m^2\ kg^{-1}$

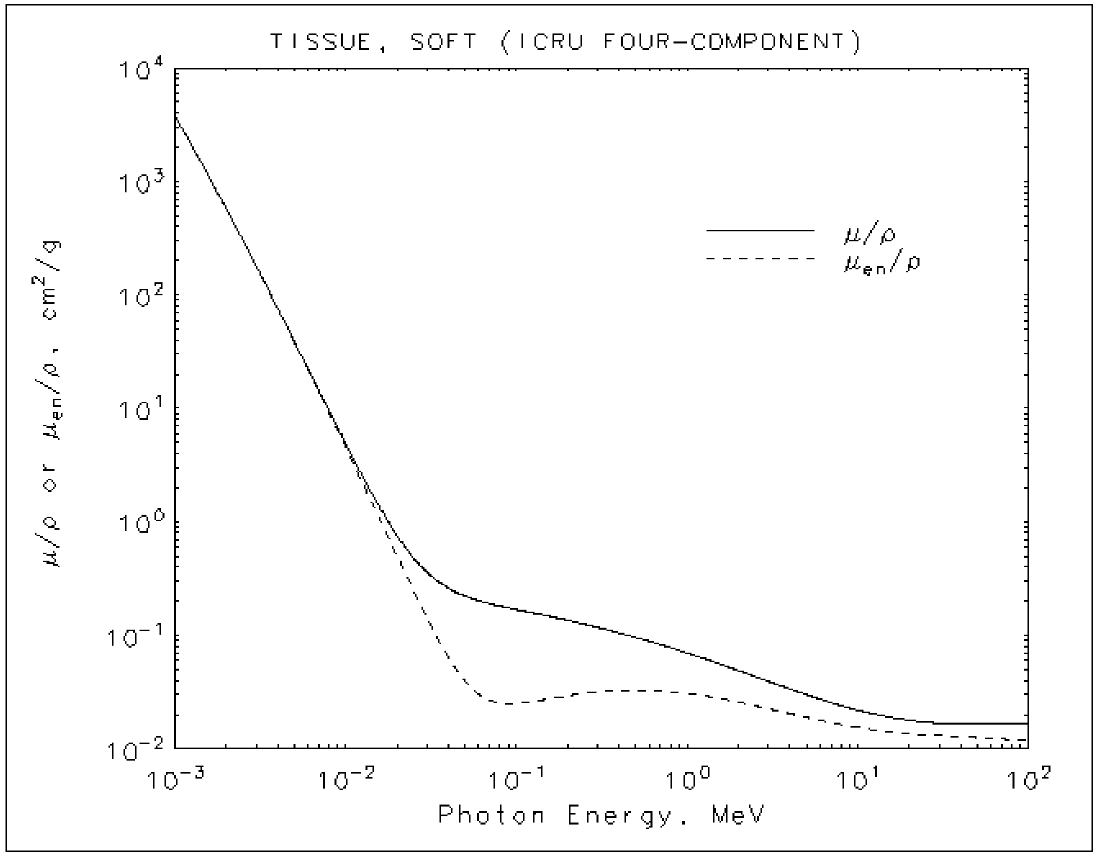


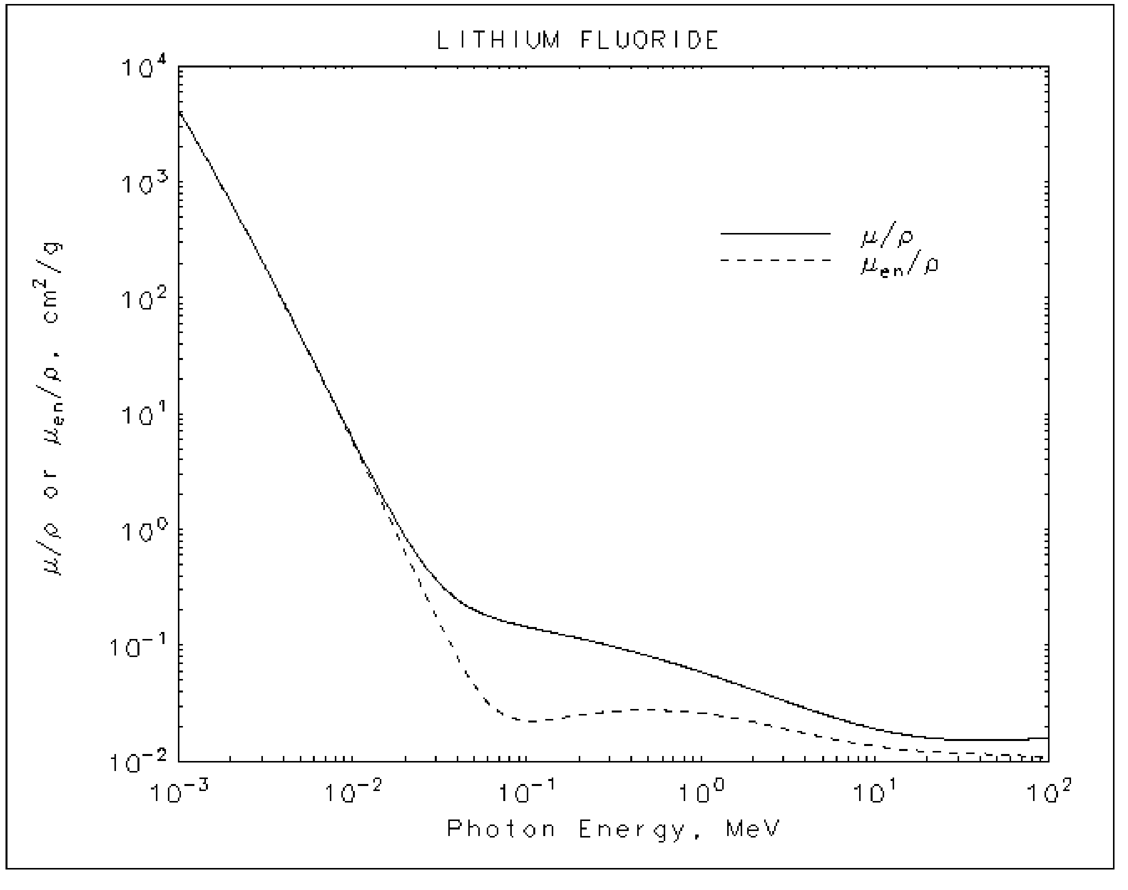


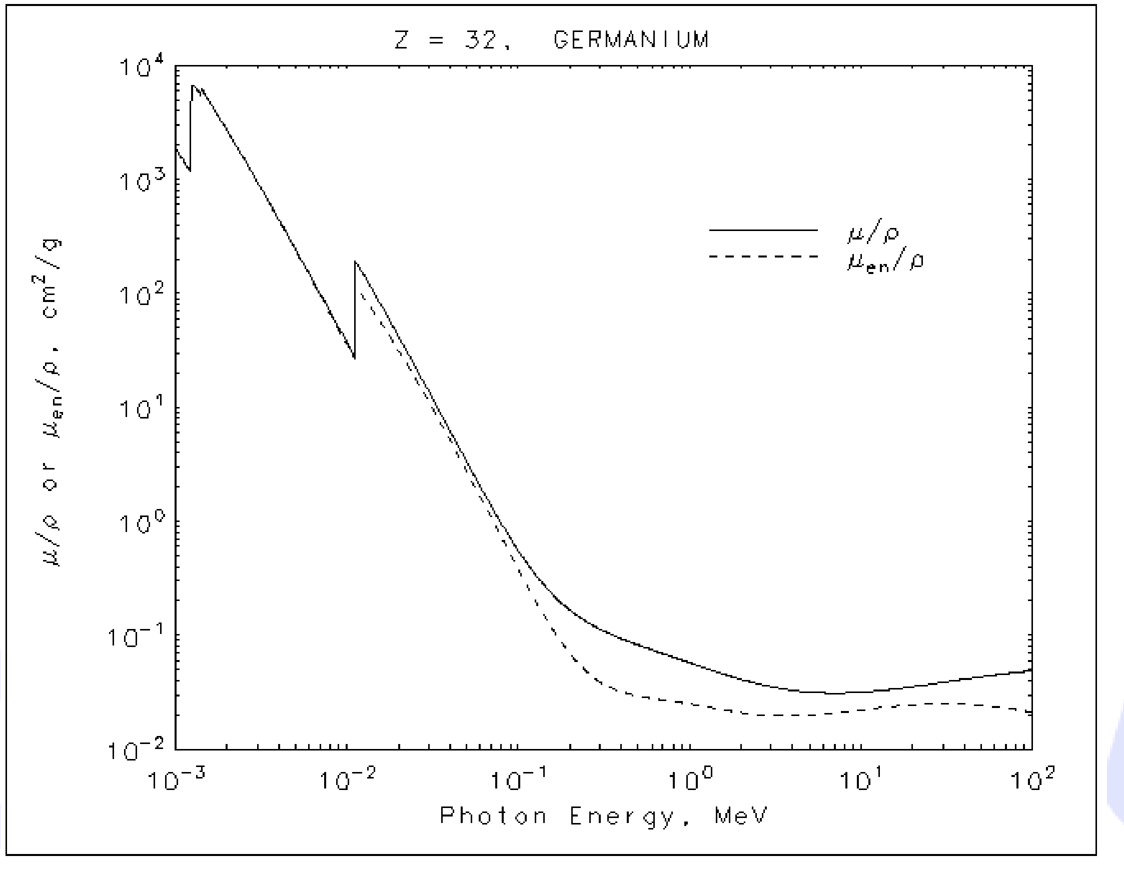
Interaction Coefficients

(https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients)





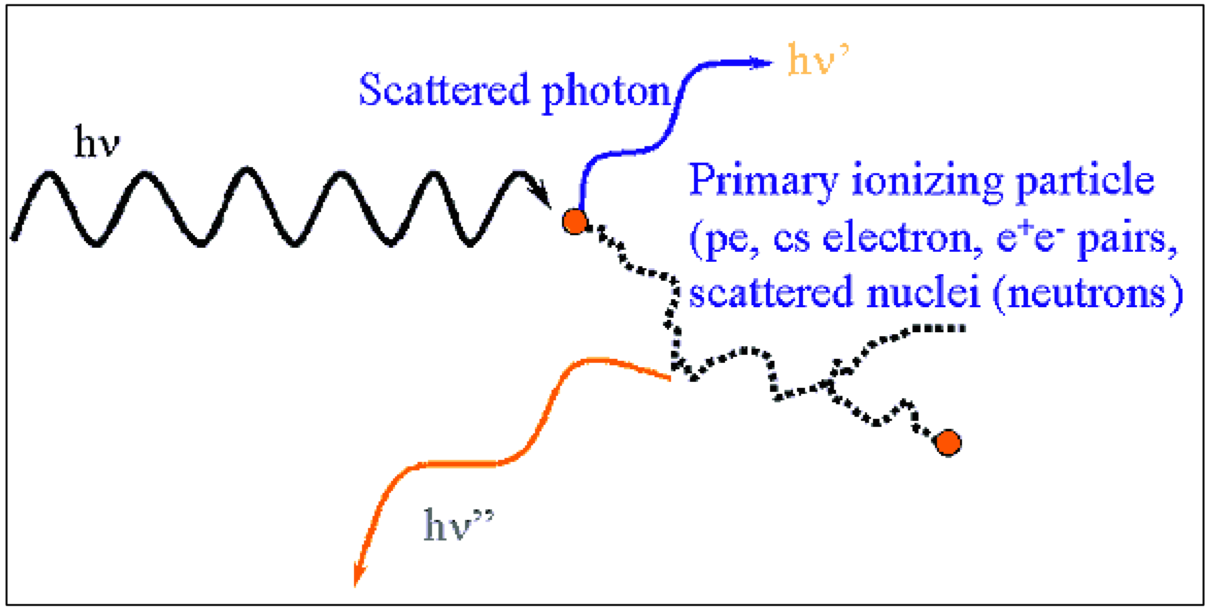




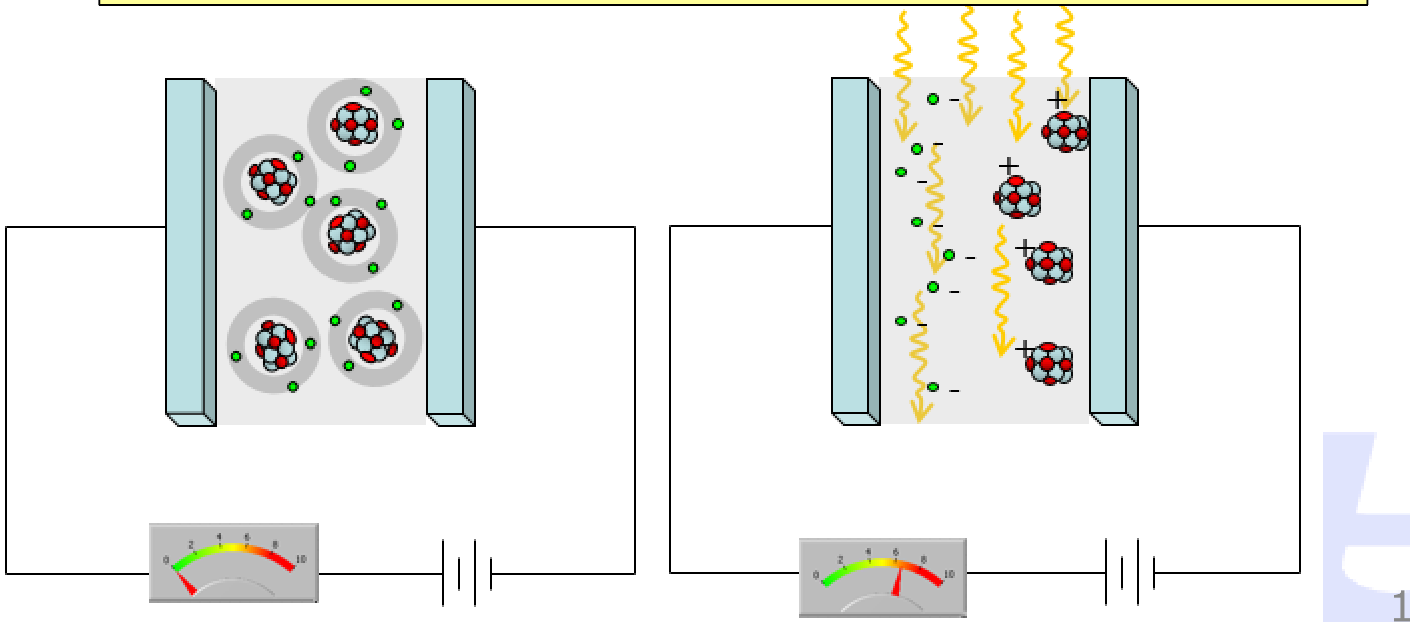
Dosimetry: Conversion of energy

Definition	Units
The **kerma, K, for ionizing uncharged particles**, is the quotient of dE_{tr} by dm, where dE_{tr} is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass dm of a material by the uncharged particles incident on dm: $$\mathbf{K = dE_{tr}/dm}$$ For a given energy E of uncharged particles: $$K = \Phi\cdot E\cdot\frac{\mu_{tr}}{\rho}=\Psi\cdot\frac{\mu_{tr}}{\rho}=K_{col}+K_{rad}=\Psi\cdot\frac{\mu_{tr}}{\rho}\cdot(1-g)+\Psi\cdot\frac{\mu_{tr}}{\rho}\cdot g=\Psi\cdot\frac{\mu_{en}}{\rho}+\frac{\mu_{en}}{\rho}\cdot\Psi\cdot\frac{g}{1-g}$$	J kg^{-1} (gray, Gy)
The **exposure, X,** is the quotient of dq by dm, where dq is the absolute value of the mean total charge of the ions of one sign produced when all the electrons and positrons liberated or created by photons incident on a mass dm of dry air are completely stopped in dry air: $$\mathbf{X = dq/dm}$$ For a given energy E of photons: $$X \approx \frac{e}{W}\cdot\Phi\cdot E\cdot\frac{\mu_{tr}}{\rho}\cdot(1-g)=\frac{e}{W}\cdot\Phi\cdot E\cdot\frac{\mu_{en}}{\rho}$$ Where e is the elementary charge and W is the mean energy expended in dry air per ion pair formed (about 34 eV).	C kg^{-1}

Kerma concept

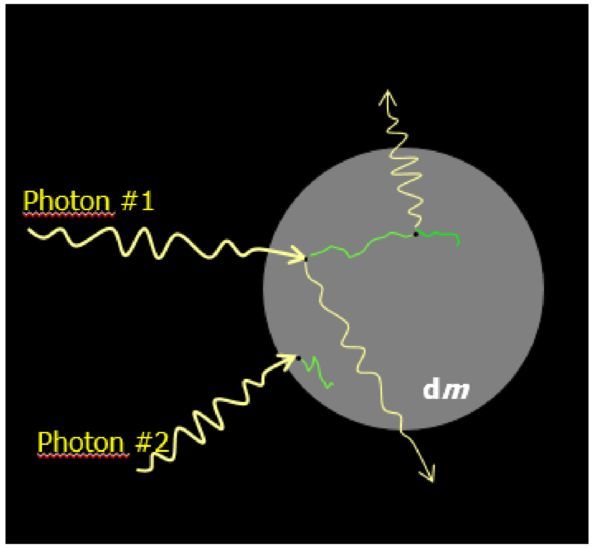


Measuring Exposure with a gas filled detector



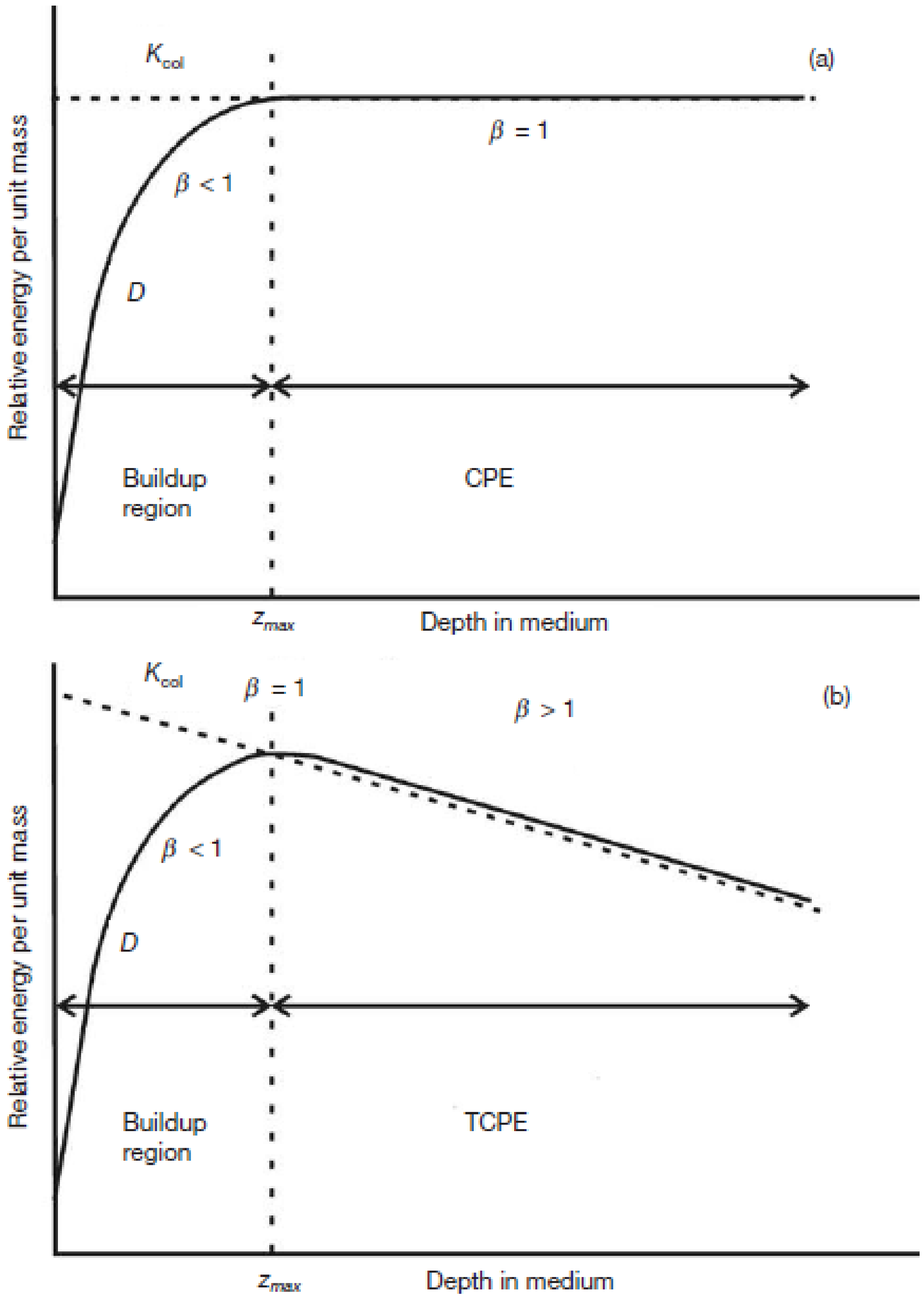
Dosimetry: Deposition of energy

Definition	Units
The **energy deposit, ε_i,** is the energy deposited in a single interaction, *i*: $$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$ where ε_{in} is the energy of the incident ionizing particle (excluding rest energy), ε_{out} is the sum of the energies of all charged and uncharged ionizing particles leaving the interaction (excluding rest energy), and Q is the change in the rest energies of the nucleus and of all elementary particles involved in the interaction (Q>0: decrease of rest energy; Q<0: increase of rest energy).	J
The **energy imparted, ε,** to the matter in a given volume is the sum of all energy deposits in the volume: $$\varepsilon = \sum_i \epsilon_i$$ where the summation is performed over all energy deposits, ε_i, in that volume.	J
The **mean energy imparted, $\bar{\epsilon}$,** to the matter in a given volume equals the mean radiant energy, R_{in}, of all charged and uncharged ionizing particles that enter the volume minus the mean radiant energy, R_{out}, of all charged and uncharged ionizing particles that leave the volume, plus the mean sum, ΣQ, of all changes of the rest energy of nuclei and elementary particles that occur in the volume (Q>0: decrease of rest energy; Q<0: increase of rest energy): $$\bar{\epsilon} = R_{in} - R_{out} + \Sigma Q$$	J
The **absorbed dose, *D*,** is the quotient of $d\bar{\epsilon}$ by d*m*, where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass d*m*: $$D = d\bar{\epsilon}/dm$$	J kg^{-1} (gray, Gy)



- **The energy of photon #1 is partly absorbed in dm, and two photons achieve to be released with a fraction of the incident energy.**
- **The energy of photon #2 is fully deposited in d*m* through the previous conversion of energy.**
- **The radiative losses are negligible.**

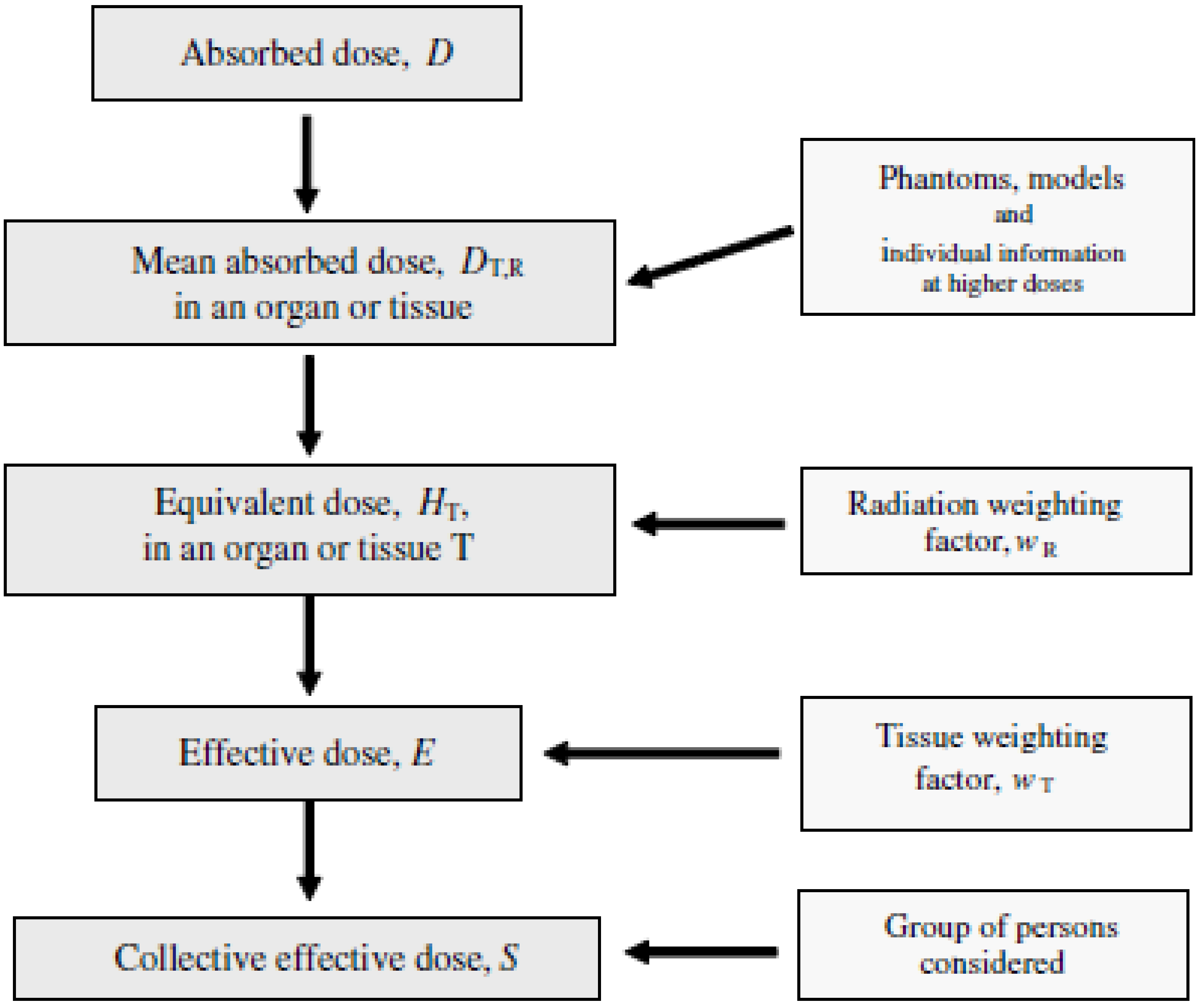
Dosimetry: Kerma and Absorbed Dose



- Generally, the **transfer of energy (kerma)** from the photon beam to charged particles at a particular location does not lead to the **absorption of energy by the medium (absorbed dose)** at the same location. This is due to the finite range of the secondary electrons released through photon interactions.
- As a high energy photon beam penetrates the medium, **collision kerma, K_{col},** is maximal at the surface of the irradiated material because photon fluence is greatest at the surface. Initially, the charged particle fluence, and hence the absorbed dose, *D*, increases as a function of depth until the depth of dose maximum z_{max}, is attained. The parameter β is defined as $\beta = D/K_{col}$.
- **(a) Charge particle equilibrium (CPE):** No photon attenuation or scattering in the medium. Buildup region with $\beta<1$ up to reach z_{max} where $\beta=1$, i.e., $D=K_{col}$.
- **(b) Transient charge particle equilibrium (TCPE):** there exists an essentially constant relation between collision kerma and absorbed dose. This relation is practically constant (with β slightly over 1) since, in high energy photon beams, the average energy of the generated electrons and hence their range does not change appreciably with depth in the medium.

Protection quantities (ICRP-103, 2007)

The protection quantities are used to specify dose limits to ensure that the occurrence of stochastic health effects is kept below unacceptable levels and tissue reactions are avoided.

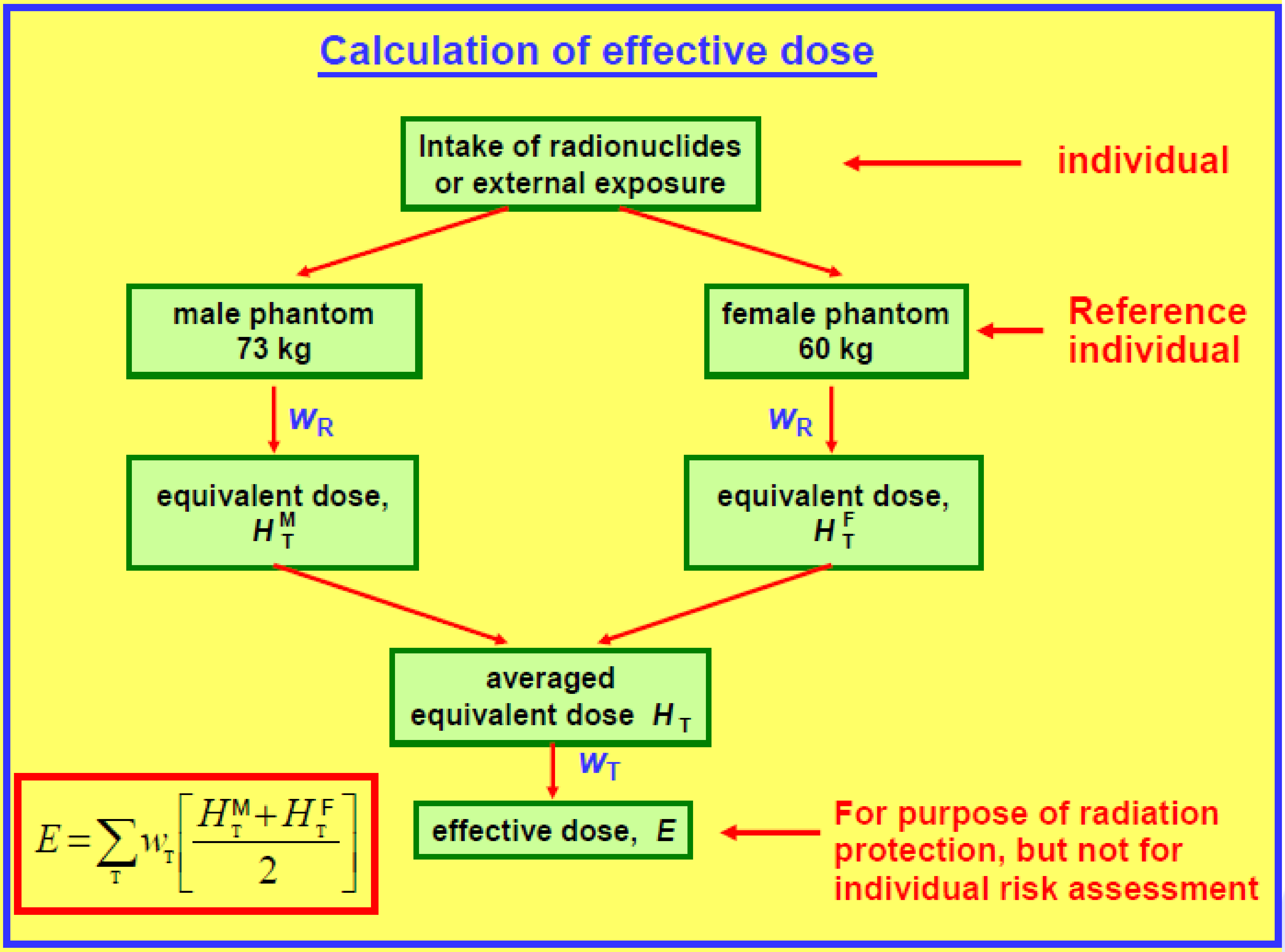


$$H_T = \sum_R w_R D_{T,R}$$

$$E = \sum_T w_T H_T = \sum_{T,R} w_T w_R D_{T,R}$$

$$S = \sum_i E_i \cdot n_i$$

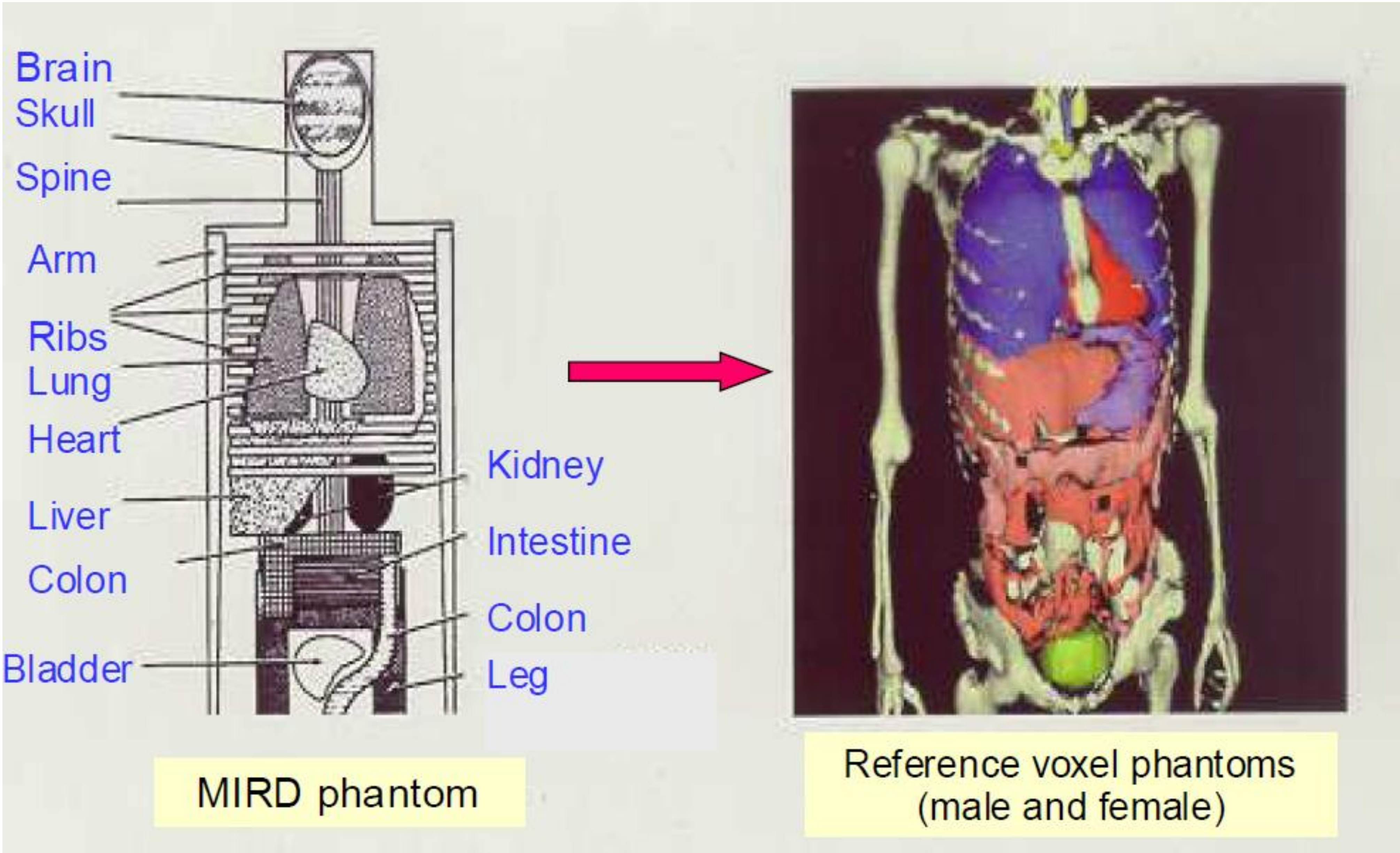
Protection quantities (ICRP-103, 2007)



$$E = \sum_T w_T \left[\frac{H_T^M + H_T^F}{2} \right]$$

Protection quantities (ICRP-103, 2007)

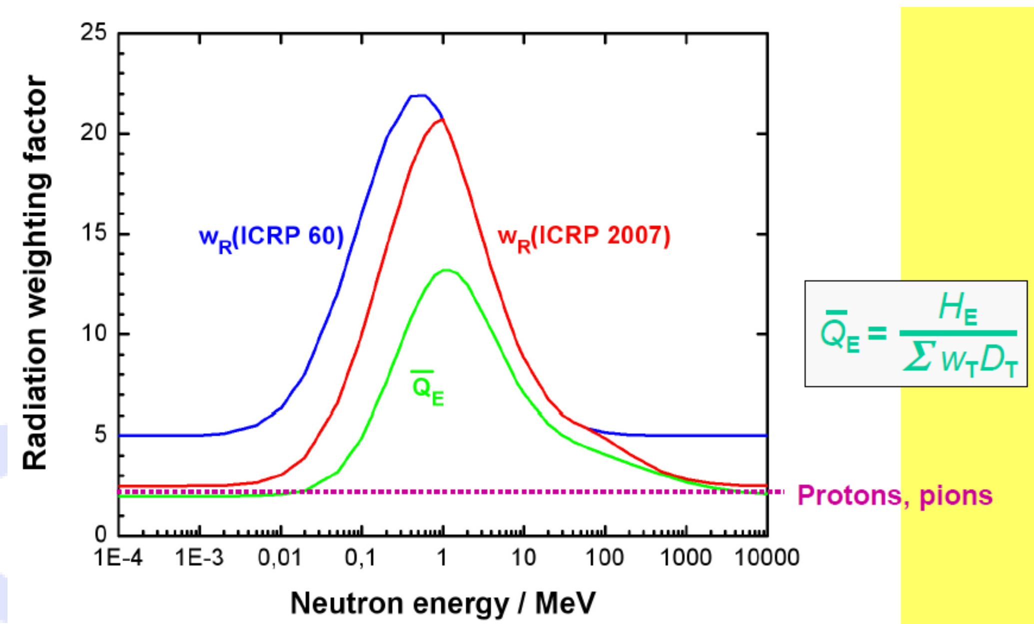
- The evaluation of equivalent doses for the Reference Male and Female, and of effective dose for the Reference Person, is based on the use of **anthropomorphic models and subsequent calculations**.
- The body-related protection quantities (equivalent dose and effective dose) **<u>are not measurable in practice</u>** and therefore cannot be used directly as quantities in radiation monitoring.



Protection quantities (ICRP-103, 2007)

Organ or tissue	ICRP-103 (2007) w_T
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Gonads	0.08
Bladder	0.04
Liver	0.04
Oesophagus	0.04
Thyroid	0.04
Bone Surface	0.01
Skin	0.01
Brain	0.01
Salivary glands	0.01
Remainder	0.12

Radiation	Energy	ICRP-103 (2007) w_R
Fotones	All	1
Electrons and muons	All	1
Neutrons	Continuous function	
Protons and charged pions	>2 MeV	2
Alpha particles, heavy ions and fission products		20



Operational quantities (ICRU-39 & 51)

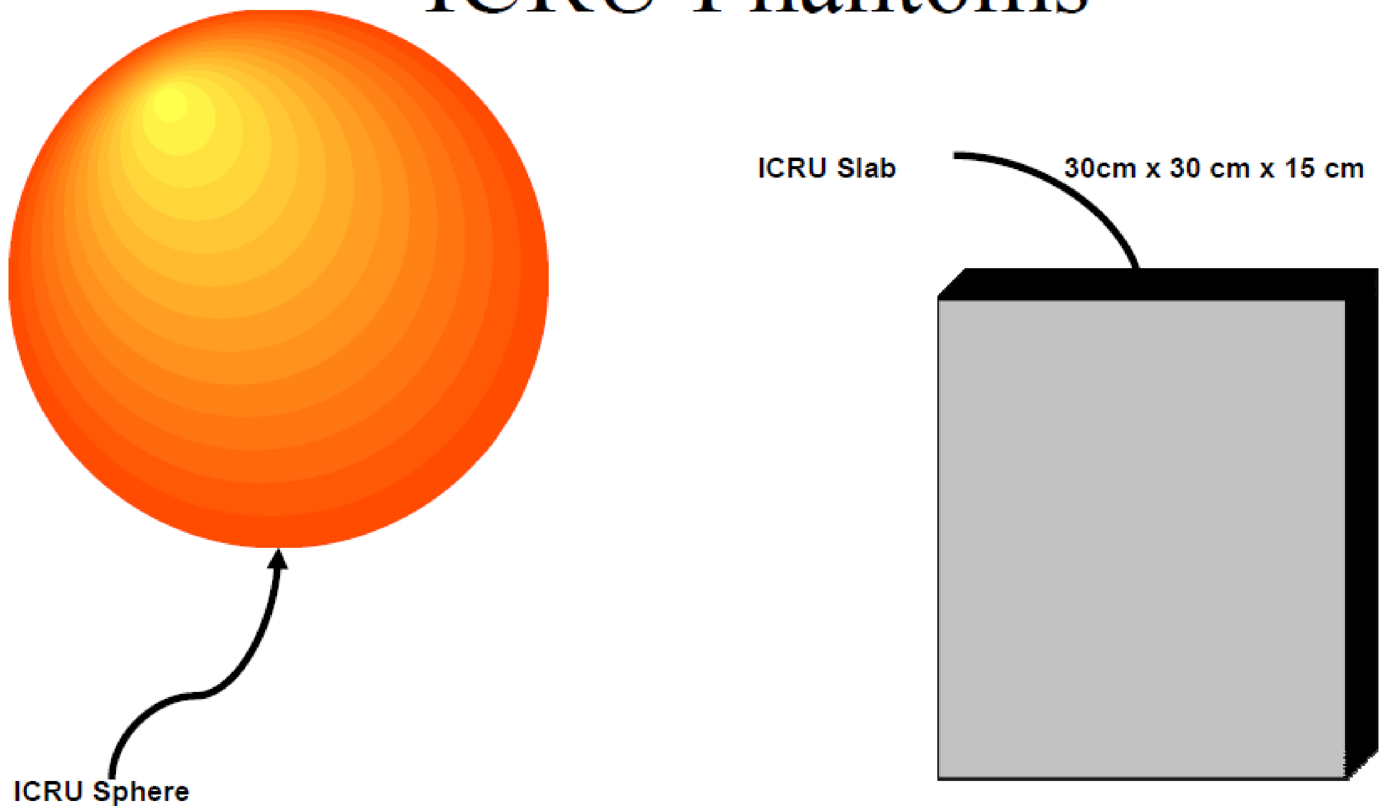
In order to provide a practicable approach for the assessment of effective dose, coefficients relating it to physical quantities, e.g., particle fluence or air kerma for external exposure, are calculated for standard conditions (e.g., mono-energetic radiations, standard irradiation geometries, selected chemical compounds labelled with radionuclides, models for the transfer of radionuclides in the body) in anthropomorphic phantoms with clearly defined geometries.

Operational quantities are aimed at providing an **estimate or upper limit for the value of the protection quantities** related to an exposure, or potential exposure of persons under most irradiation conditions. They are often used in practical regulations or guidance.

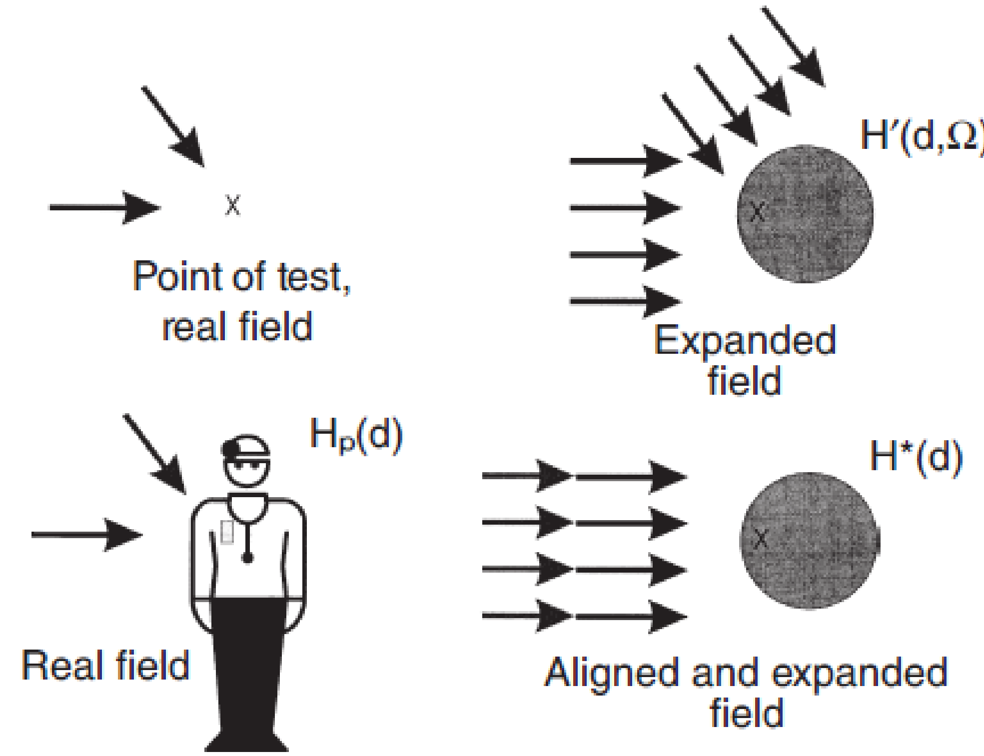
Definition	Units
The **ambient dose equivalent, H*(d),** at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth d on the radius opposing the direction of the aligned field.	$J\ kg^{-1}$ (sievert, Sv)
The **directional dose equivalent, H'(d,Ω),** at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth, d, on a radius in a specified direction, Ω.	$J\ kg^{-1}$ (sievert, Sv)
The **personal dose equivalent, Hp(d),** is the dose equivalent in soft tissue at an appropriate depth, d, below a specified point on the human body.	$J\ kg^{-1}$ (sievert, Sv)
NOTE: It is recommended to take the value d=10 mm for strongly penetrating radiations, d=3 mm for the lens eye monitoring and d=0.07 for the skin, and denoting as H*(10), H*(3) or H*(0.07), etc	

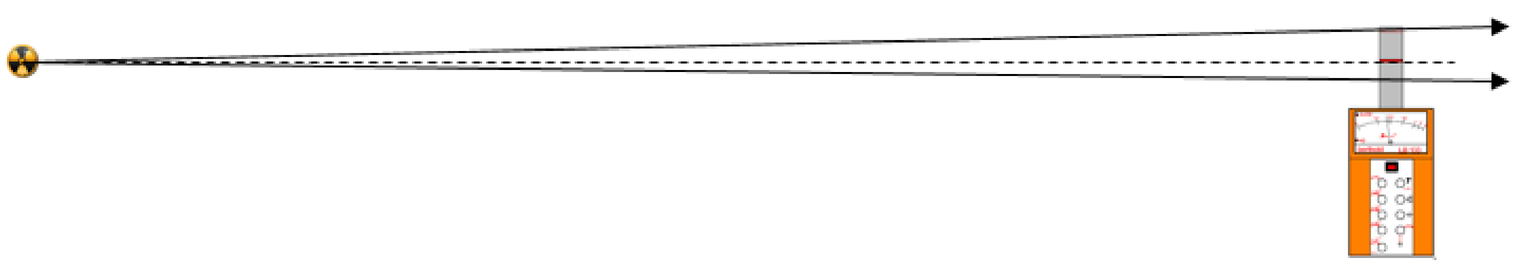
Operational quantities (ICRU-39 & 51)

ICRU Phantoms

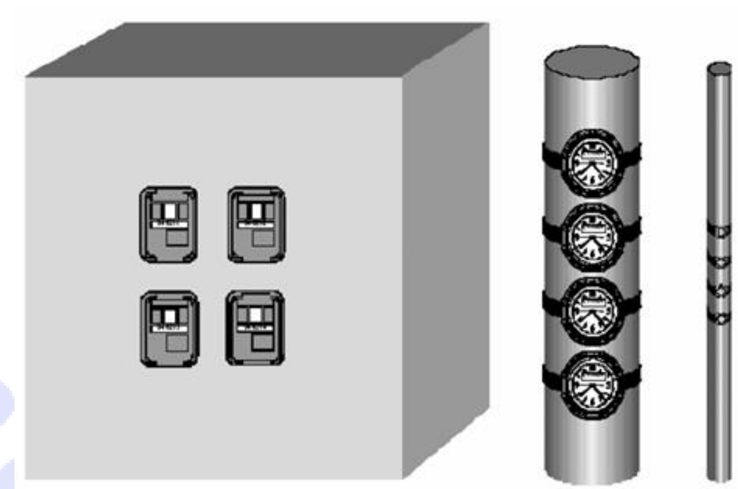


A sphere of 30 cm diameter made of *tissue equivalent material* with a density of 1 g/cm3 and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.



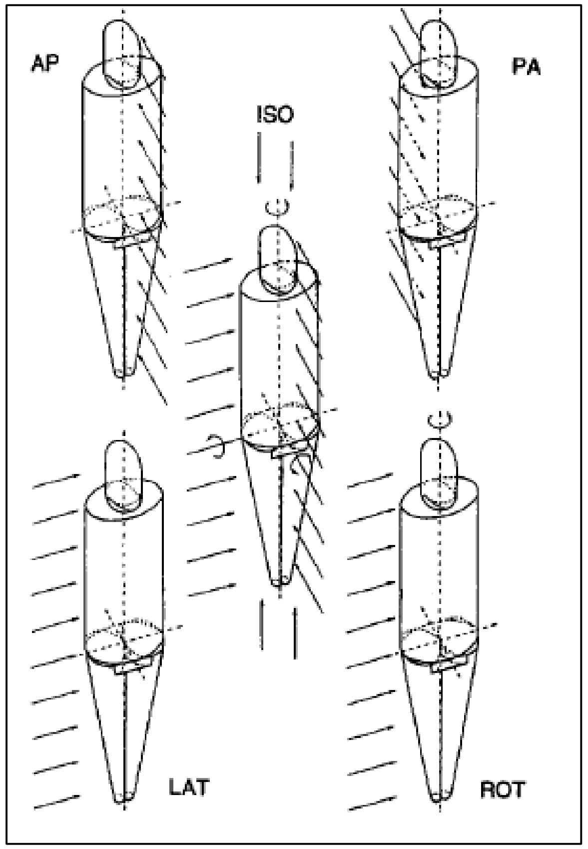


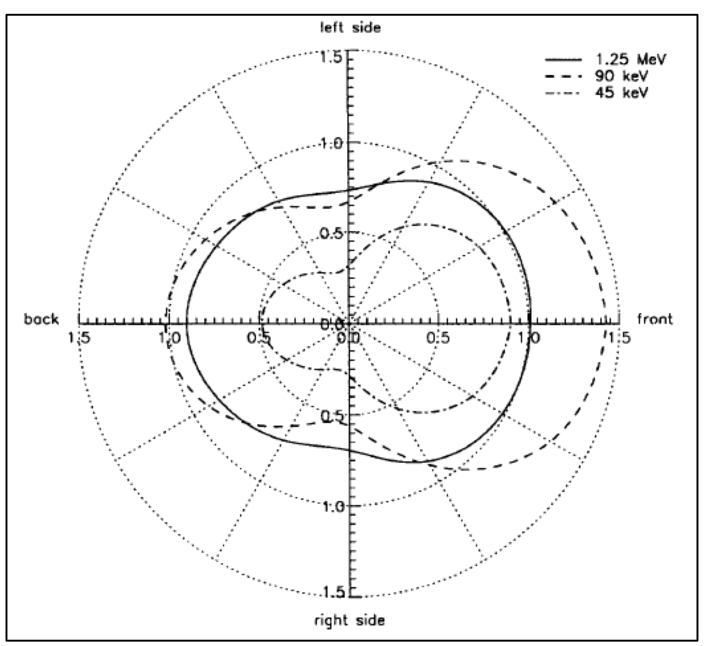
Calibration of area monitoring instruments in terms of H*(10)



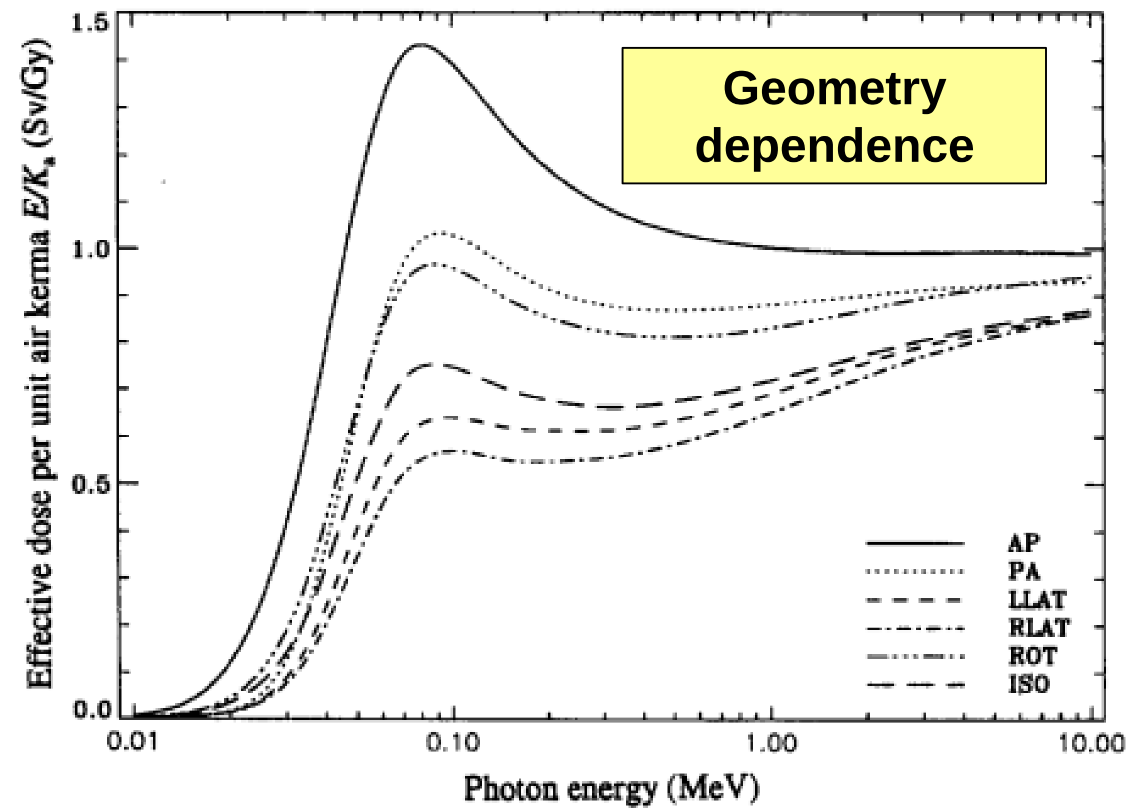
Phantoms for the calibration of personal dosemeters in terms of Hp(d)

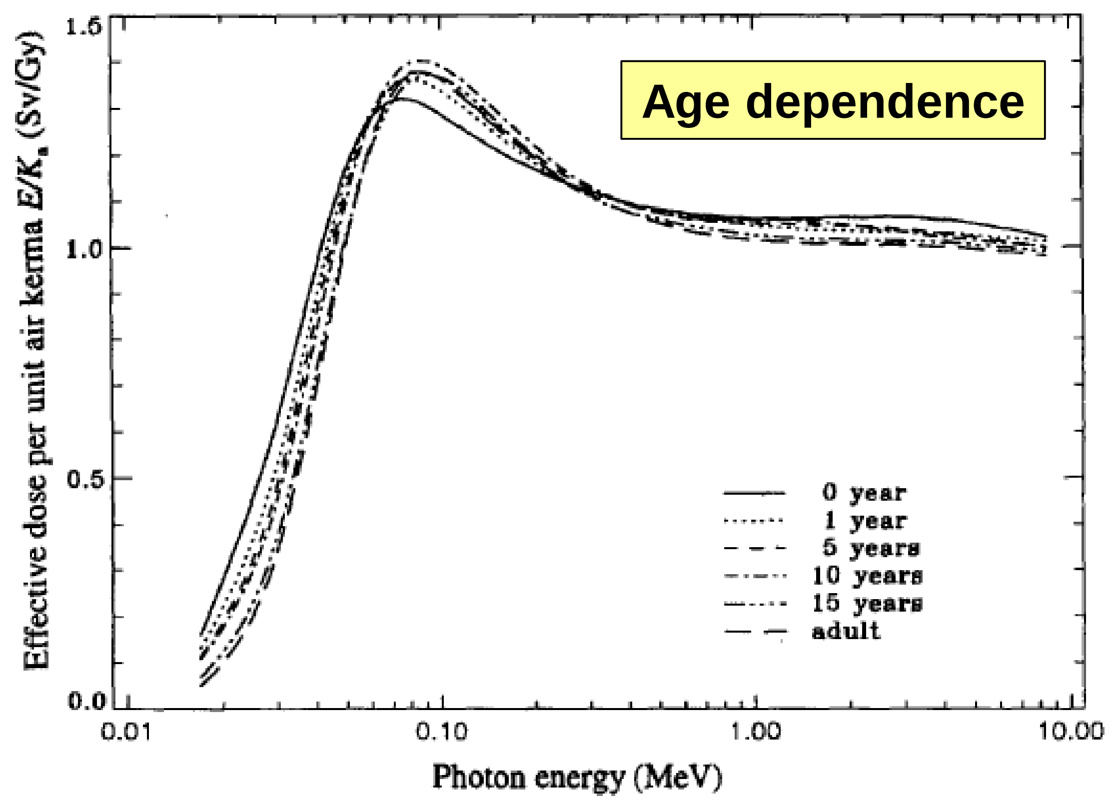
Conversion factors for operational quantities (ICRU-57 & ICRP 74, 1995)



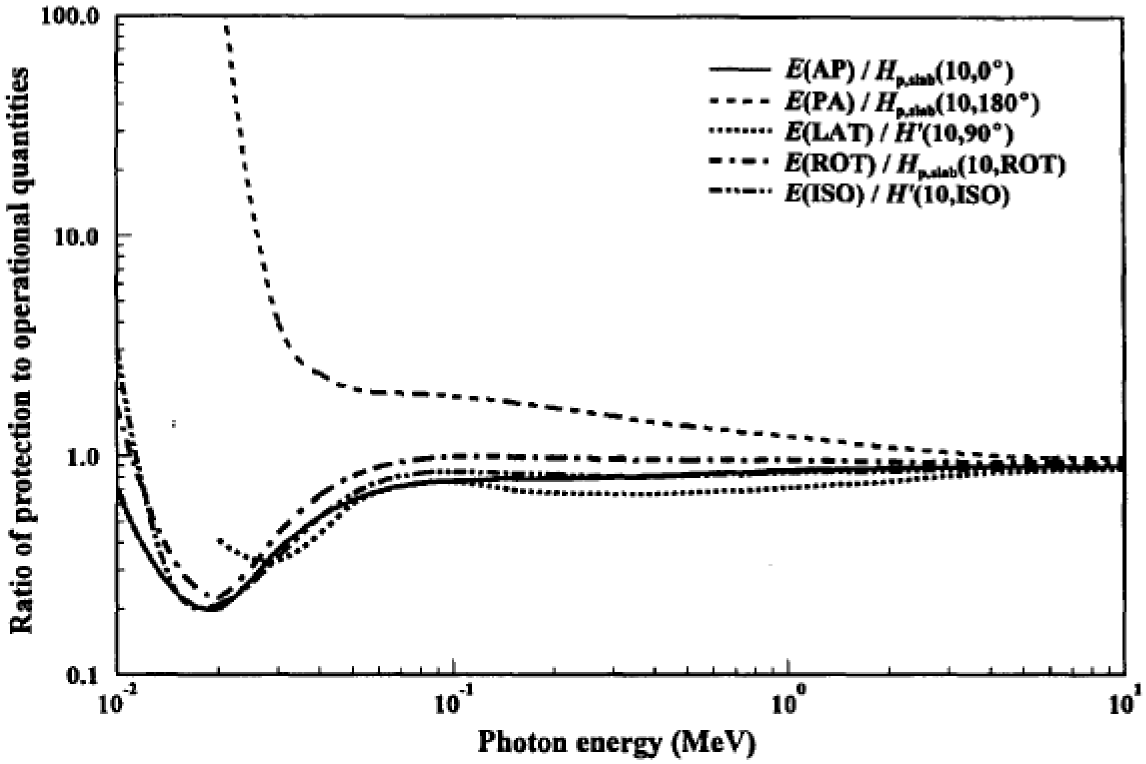


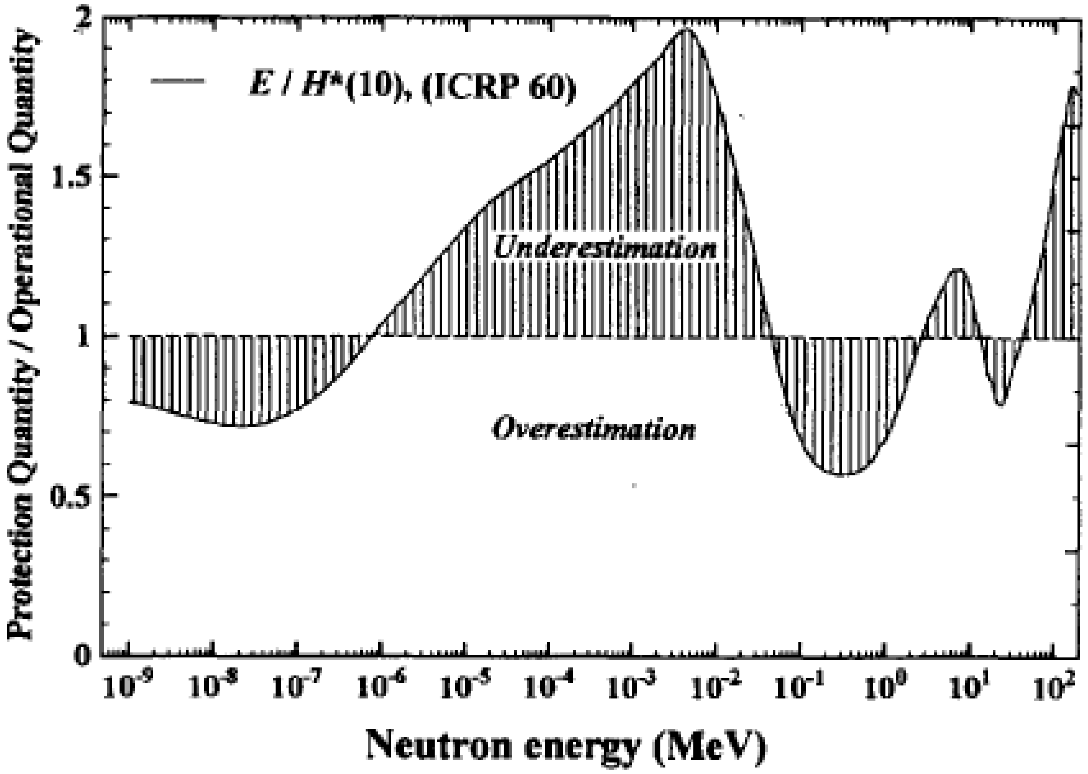
Angular dependence

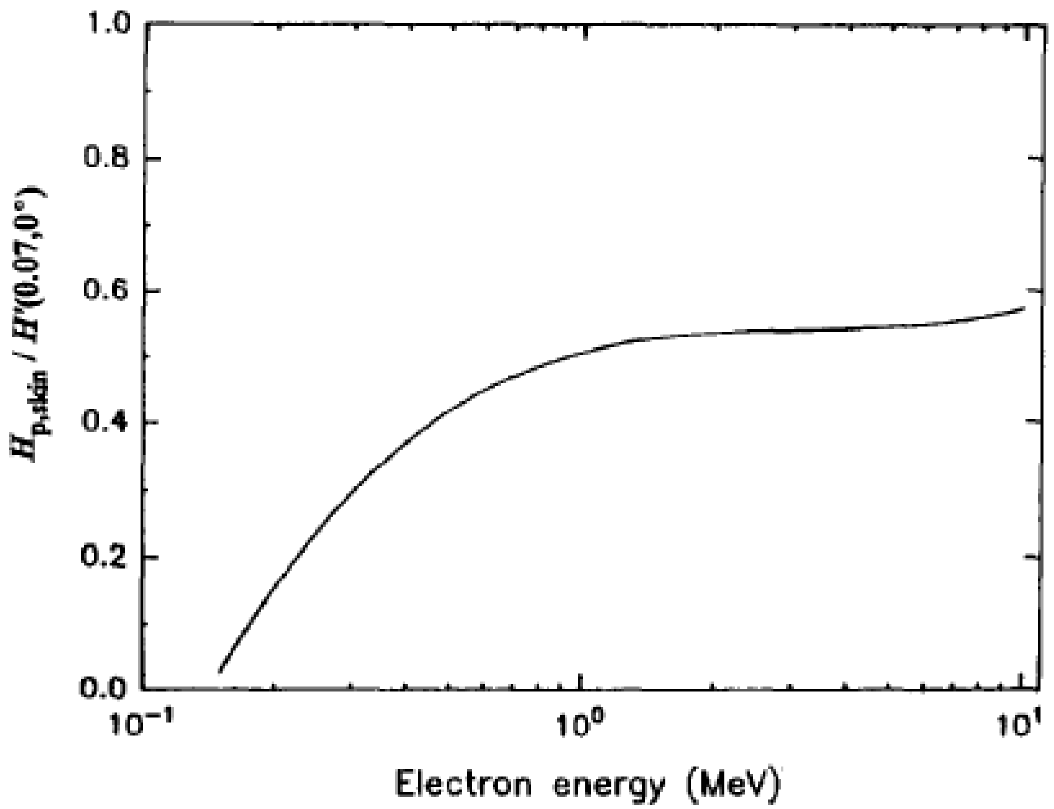




Conversion factors for operational quantities (ICRU-57 & ICRP 74, 1995)

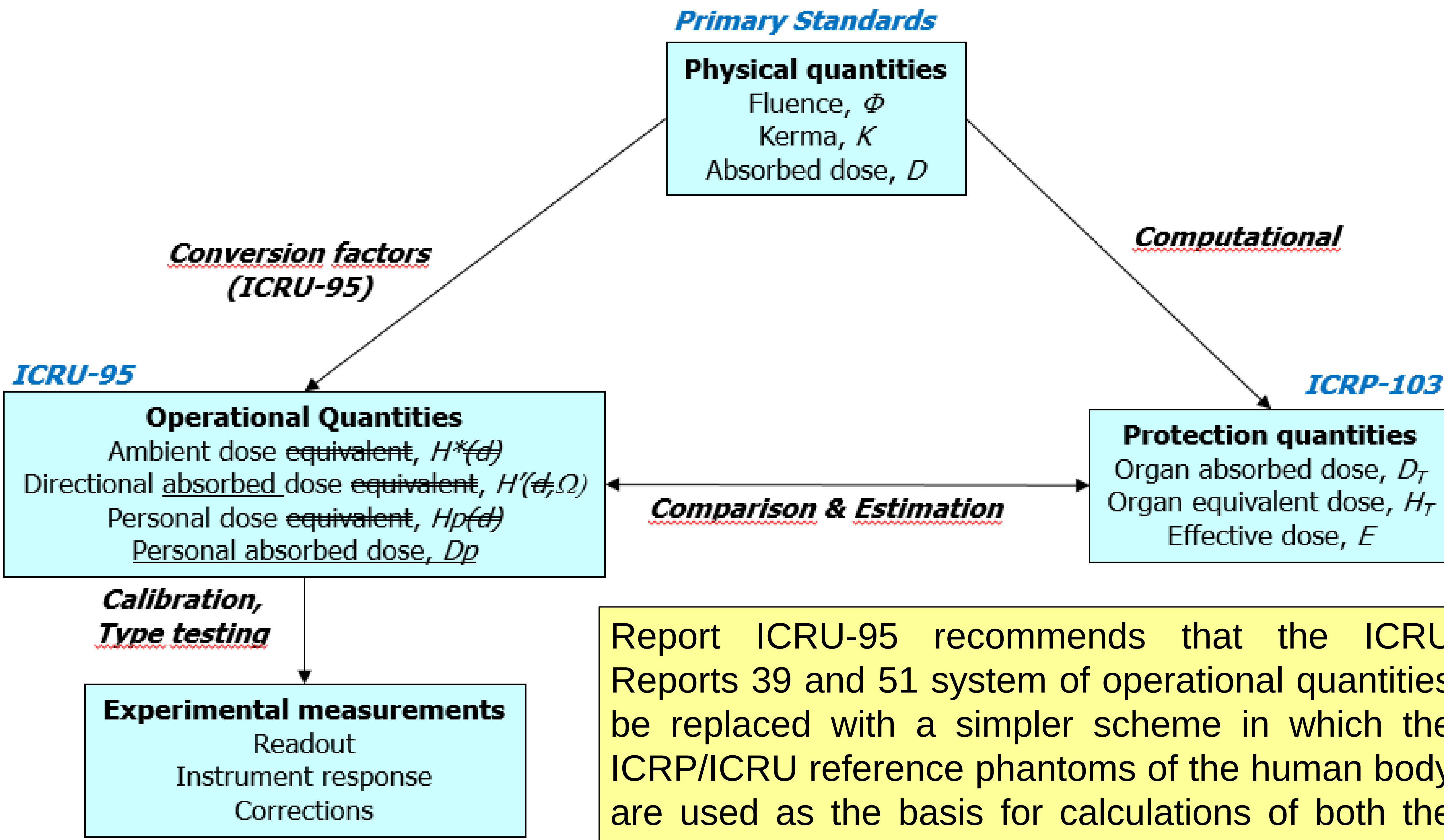






- 47 tables on the conversion factors to absorbed dose in tissues or organs from air kerma or fluence in five geometries.
- About 100 figures with tabulated data and comparison to effective dose.
- For most applications, these conversion factors provide an acceptable conservative of the protection quanties.
- In some applications (air & space dosimetry, High- energy fields), the conservative label is not reached.

ICRU-95: Operational quantities for external radiation exposure (2020)



Report ICRU-95 recommends that the ICRU Reports 39 and 51 system of operational quantities be replaced with a simpler scheme in which the ICRP/ICRU reference phantoms of the human body are used as the basis for calculations of both the operational and protection quantities, ensuring that the operation quantities provide measures of the protection quantities across all energy ranges.

ICRU-95: Operational quantities for external radiation exposure (2020)

$$H_R(\Omega) = \int h_R(E_p,\Omega)\cdot\Phi_R(E_p,\Omega)\, dE_p$$

- Numerical values of ambient dose and personal dose are by definition numerically identical to particular values of effective dose at equal energy and angle of incidence.
- Extended energy ranges for several radiations.
- A brand new set of conversion coefficients from physical quantities is provided.

Definition	Units
The **ambient dose, *H*,*** at a point in a radiation field, is the product of the particle fluence at that point, $\boldsymbol{\Phi}$, and the conversion coefficient, ***h*,*** relating particle fluence to the maximum value of effective dose, E_{max}, for various irradiation conditions.	J kg^{-1} (sievert, Sv)
The **directional absorbed dose in the lens of the eye,** $\boldsymbol{D'_{lens}(\Omega)}$, a point in a radiation field with a specified direction of incidence, $\boldsymbol{\Omega}$, is the product of the particle fluence at that point, Φ(Ω), and the conversion coefficient, $\boldsymbol{d'_{lens}(\Omega)}$, relating particle fluence to the value of absorbed dose in the lens of the eye.(*)	J kg^{-1} (gray, Gy)
The **personal dose,** $\boldsymbol{H_p}$, at a point on the body is the product of the particle fluence incident at that point, $\boldsymbol{\Phi}$, and the conversion coefficient, $\boldsymbol{h_p}$, relating particle fluence to the value of effective dose, E.	J kg^{-1} (sievert, Sv)
The **personal absorbed dose in the lens of the eye,** $\boldsymbol{D_{p\ lens}}$, at a point on the head or body is the product of the particle fluence incident at that point, $\boldsymbol{\Phi}$, and the conversion coefficient, $\boldsymbol{d_{p\ lens}}$, relating particle fluence to the value of absorbed dose in the lens of the eye.(*)	J kg^{-1} (gray, Gy)
(*) Similar definitions and the same units are stated for **directional absorbed dose in local skin,** $\boldsymbol{D'_{local\ skin}(\Omega)}$, and **personal absorbed dose in local skin,** $\boldsymbol{D_{p\ local\ skin}}$	

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Table 4.1 Symbols used for conversion coefficients in the figures of Section 4 and the appendices.

Symbol	Physical identity	Name of conversion coefficient
h^*	H^*/Φ	Fluence to ambient dose
$h^*(10)$	$H^*(10)/\Phi$	Fluence to *ambient dose equivalent*
$h_p(\varphi)$	$H_p(\varphi)/\Phi$	Fluence to personal dose
$h_p(10,\varphi)$	$H_p(10,\varphi)/\Phi$	Fluence to *personal dose equivalent* at 10 mm depth
$d'_{lens}(\varphi)$	$D'_{lens}(\varphi)/\Phi$	Fluence to directional absorbed dose in the lens of the eye
$h'(3,\varphi)$	$H'(3,\varphi)/\Phi$	Fluence to *directional dose equivalent* at 3 mm depth
$d_{p\ lens}(\varphi)$	$D_{p\ lens}(\varphi)/\Phi$	Fluence to personal absorbed dose in the lens of the eye
$h_p(3,\varphi)$	$H_p(3,\varphi)/\Phi$	Fluence to *personal dose equivalent* at 3 mm depth
$d'_{local\ skin}(\varphi)$	$D'_{local\ skin}(\varphi)/\Phi$	Fluence to directional absorbed dose in local skin
$h'(0.07,\varphi)$	$H'(0.07,\varphi)/\Phi$	Fluence to *directional dose equivalent* at 0.07 mm depth
$d'_{local\ skin}(\varphi)$	$D_{p\ local\ skin}(\varphi)/\Phi$	Fluence to personal absorbed dose in local skin
$h_p(0.07,\varphi)$	$H_p(0.07,\varphi)/\Phi$	Fluence to *personal dose equivalent* at 0.07 mm depth

The names of the ICRU Report 39/51 operational quantities are in italics.

If a change intervenes in the conventional quantity value ***Q***, for example, by a new definition of the quantity, then the new response ***R*** can be calculated from the known, old response, $R_{old}=M/Q_{old}$ via the old and new conversion coefficients, h_{old} and ***h***, respectively, by:

$$R = \frac{M}{Q_{old}}\frac{Q_{old}}{Q} = R_{old}\frac{Q_{old}}{Q} = R_{old}\frac{h_{old}}{h}$$

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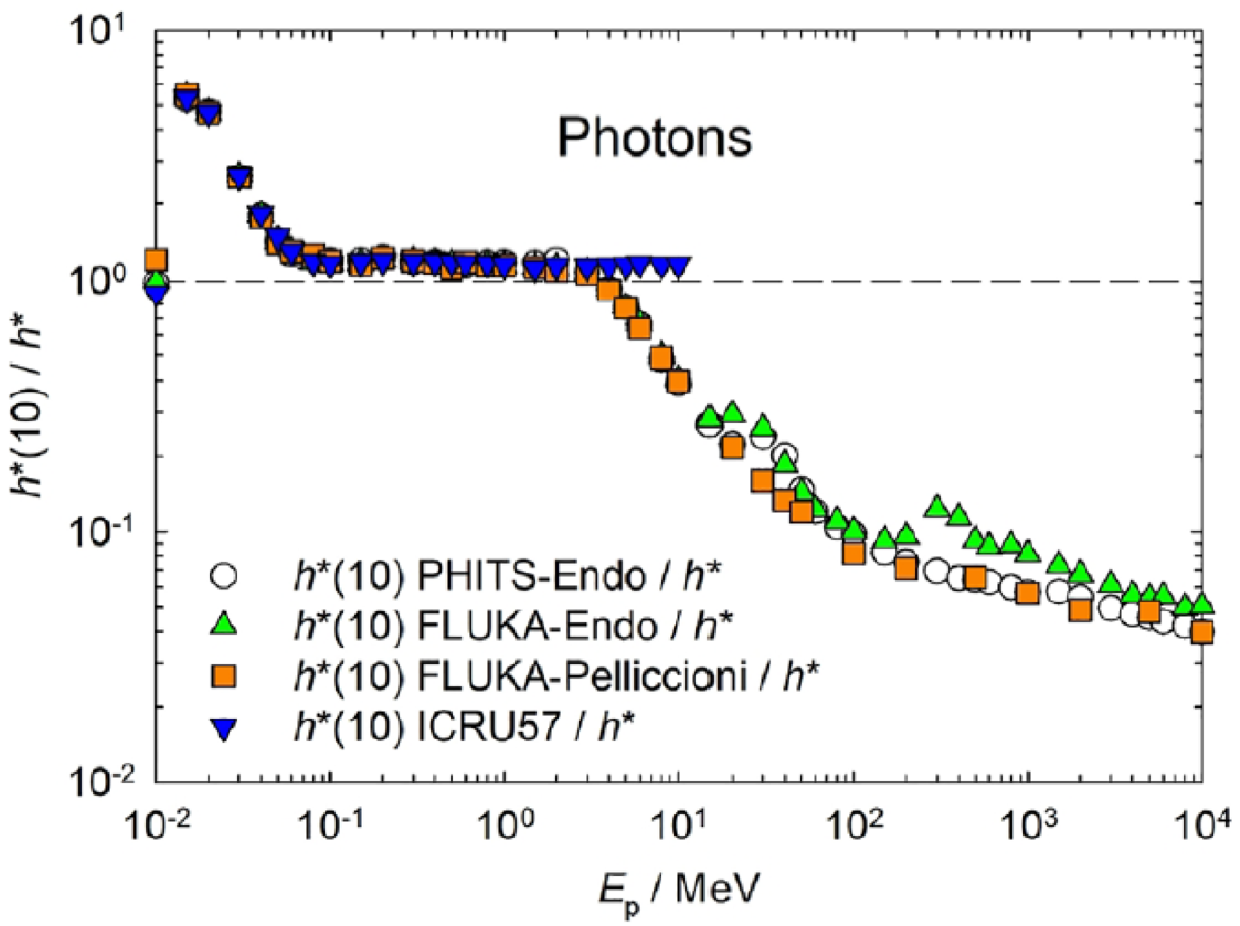

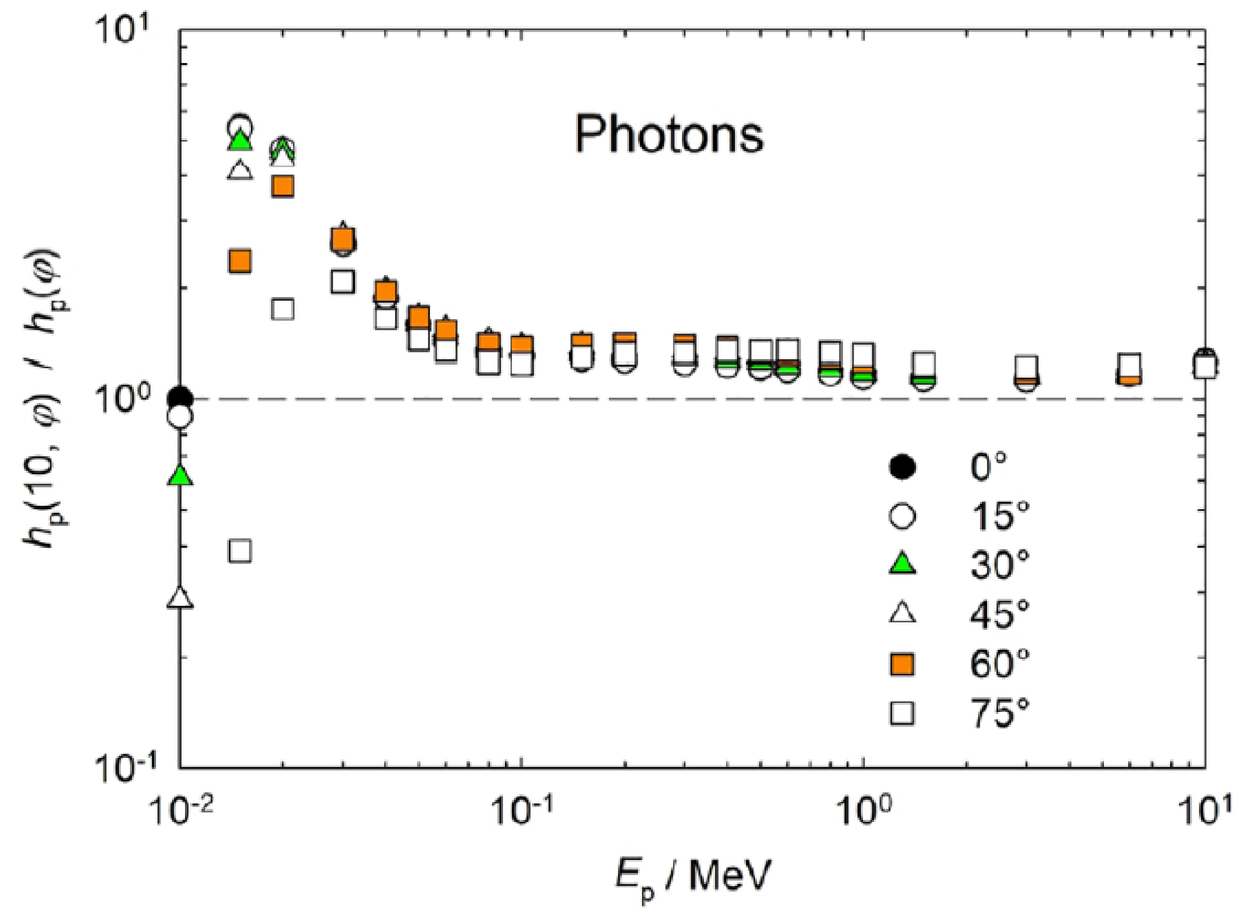

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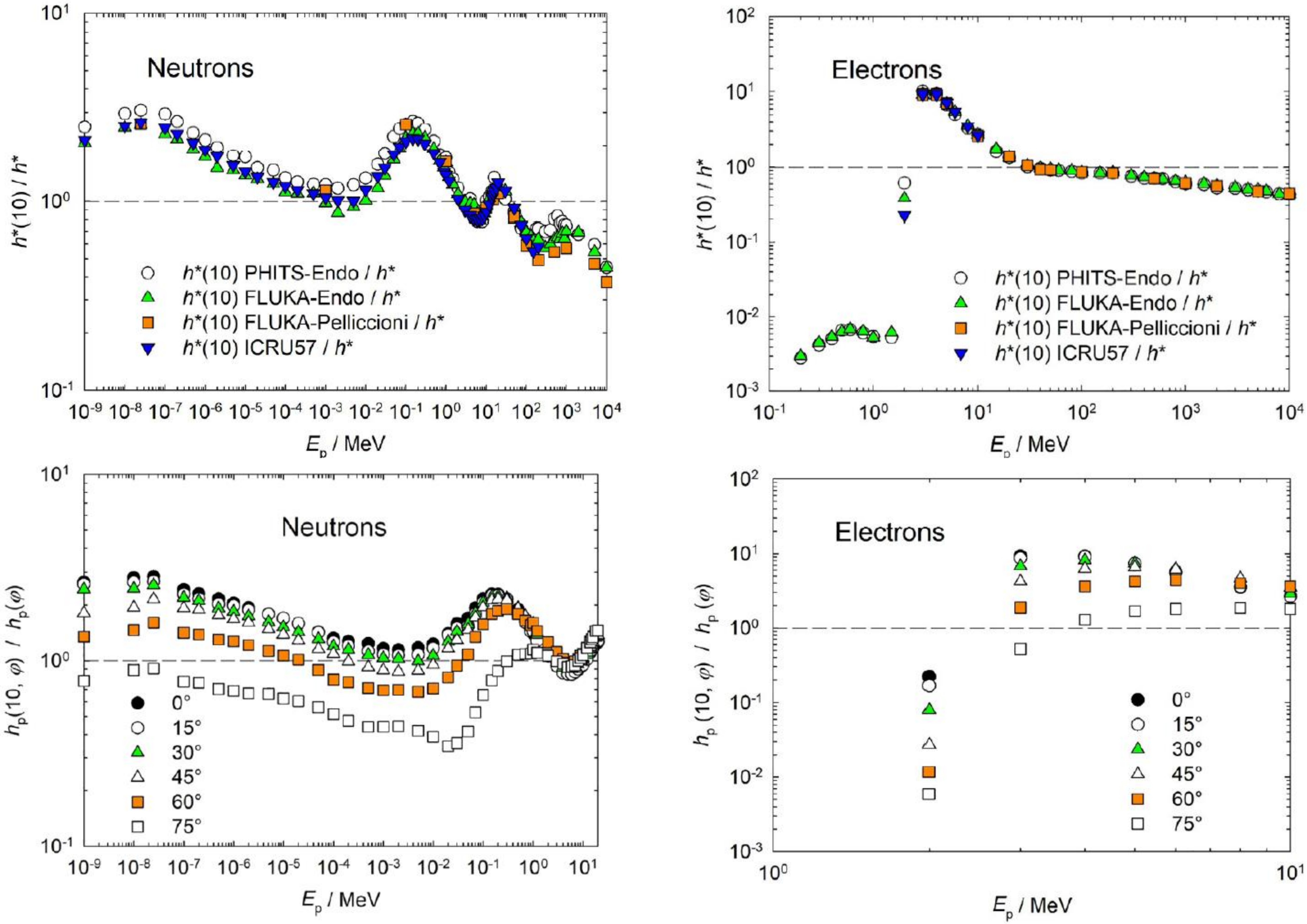

ICRU-95: Operational quantities for external radiation exposure (2020)

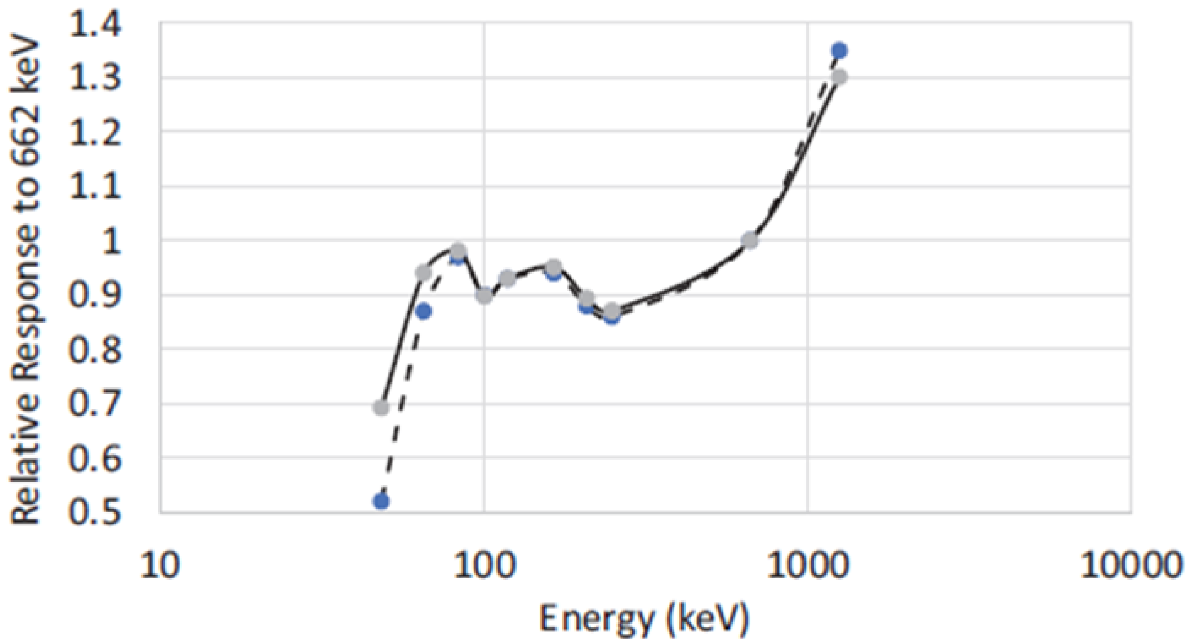

Figure 5.1 Response relative to that at 662 keV for ambient dose H^* (solid line) and ambient dose equivalent $H^*(10)$ (dashed line) of a commercially available area monitoring instrument based on a Geiger-Müller counter (adapted from Otto, 2019).

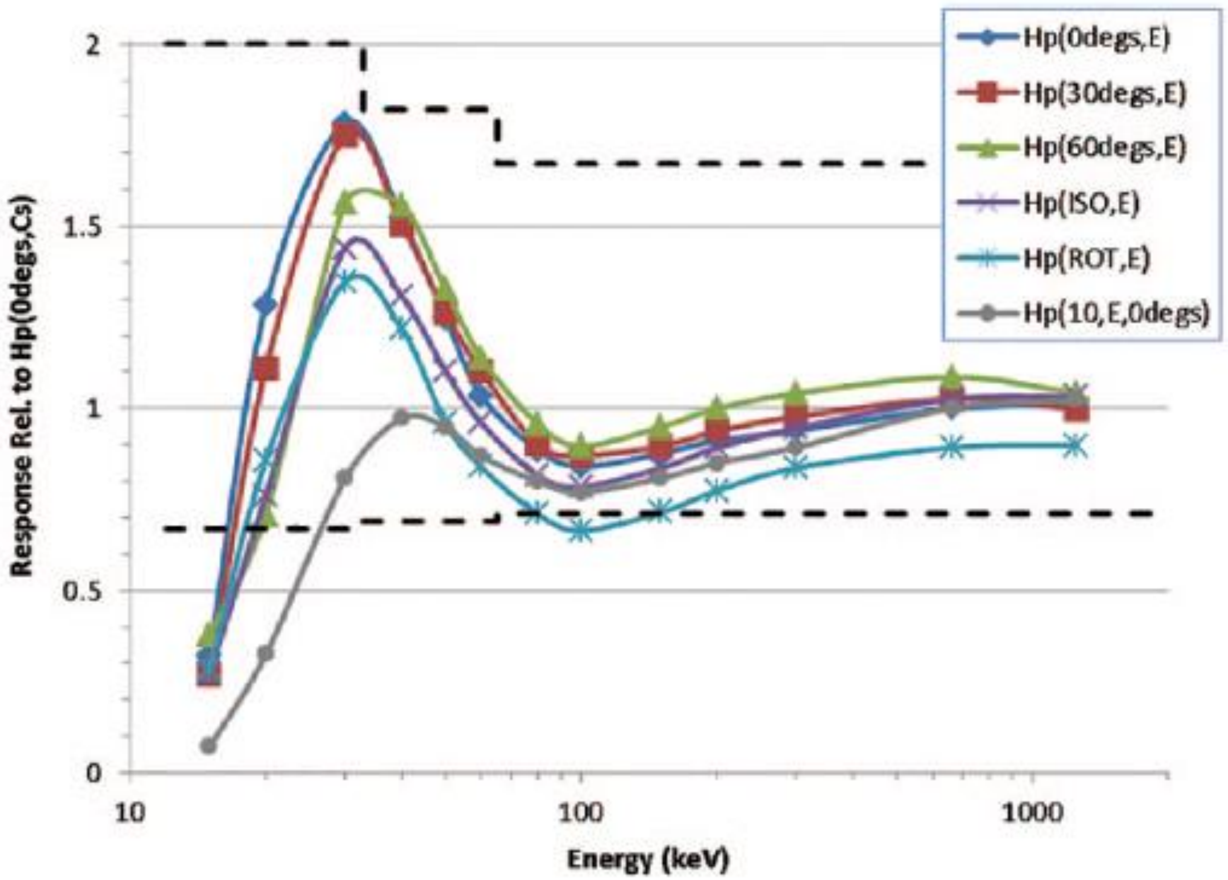

Figure 5.2 $H_p(\phi)$ response of the redesigned thermoluminescent dosimeter relative to its $H_p(0°, Cs)$ response.

Note. Also shown is the $H_p(10, 0°)/H_p(10,0°, Cs)$ relative response of the redesign (Eakins and Tanner, 2019).

Some modifications could be needed in the design or algorithm of existing instrumentation.

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