Assessment of Occupational Exposure due to External Radiation Sources

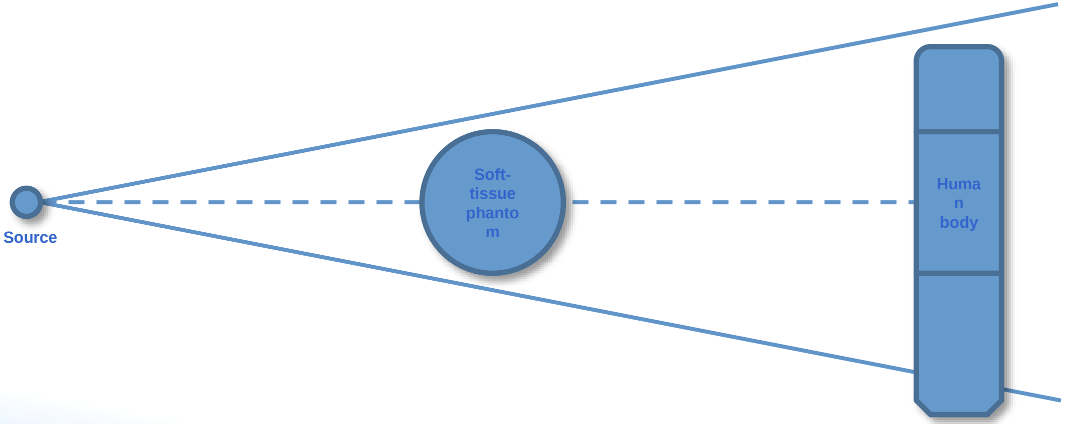
Dosimetric Quantities and Units

Dosimetric Quantities and Units - Unit outline

- Physical Quantities
- Protection Quantities
- Operational Quantities
- Relation between quantities: Conversion Coefficients
- Future new operational quantities

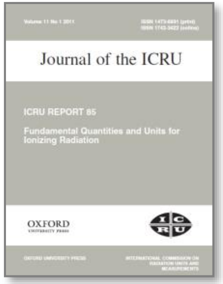
System of Quantities for Radiation Protection

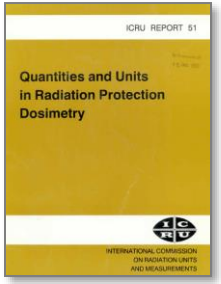
Physical quantities	Operational quantities	Protection quantities
Fluence and energy fluence, Φ, Ψ	Ambient dose equivalent, $H^*(d)$	Equivalent dose in organ, H_T
Kerma, K	Personal dose equivalent, $H_p(d)$	Effective dose, E
Absorbed dose, D	Directional dose equivalent, $H'(d,\Omega)$	Committed doses, $H_T(\tau)$,
$E(\tau)$		
Exposure, X		

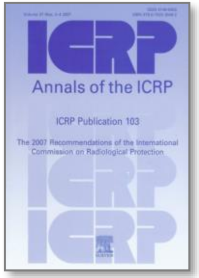


Specific roles for ICRU and ICRP

Dose quantities		
basic physical quantities	**operational quantities**	**protection quantities**
Fluence (m^{-2}) Kerma (Gy) Absorbed dose (Gy)	Dose equivalent (Sv) Ambient dose equivalent (Sv) Directional dose equivalent (Sv) Personal dose equivalent (Sv)	Equivalent dose for organs and tissues (Sv) Effective dose for the whole body (Sv)
Realised by **primary standards**	Measured with a calibrated **routine dosemeter**	Quantity for which **dose limits** are stated
Defined by ICRU		Defined by ICRP







ICRU reports
International Commission on Radiological Units and measurements

Annals of the ICRP
International Commission on Radiological Protection

Physical Quantities

Radiometic quantities:
Description of the radiation field

Flux (s^{-1}): $\varphi = \frac{dN}{dt}$

Fluence (m^{-2}): $\Phi = \frac{dN}{da}$

Fluence rate ($s^{-1}m^{-2}$): $\phi = \frac{d\Phi}{dt}$

Energie fluence (Jm^{-2}): $\Psi = \frac{dE}{da}$

Energy fluence rate ($Js^{-1}m^{-2}$): $\psi = \frac{d\Psi}{dt}$

Kerma, K

The quantity *kerma* (**k**inetic **e**nergy **r**elease in **ma**ss), K, is defined as:

$$K = \frac{dE_{tr}}{dm}$$

where dE_{tr} is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a volume of mass dm

Kerma in air, K_a, is used for radiation protection measurement purposes

The SI unit of kerma is the joule per kilogram (J/kg), termed gray (Gy)

Absorbed dose, D

The fundamental dosimetric quantity *absorbed dose*, D, is defined as:

$$D = \frac{d\varepsilon}{dm}$$

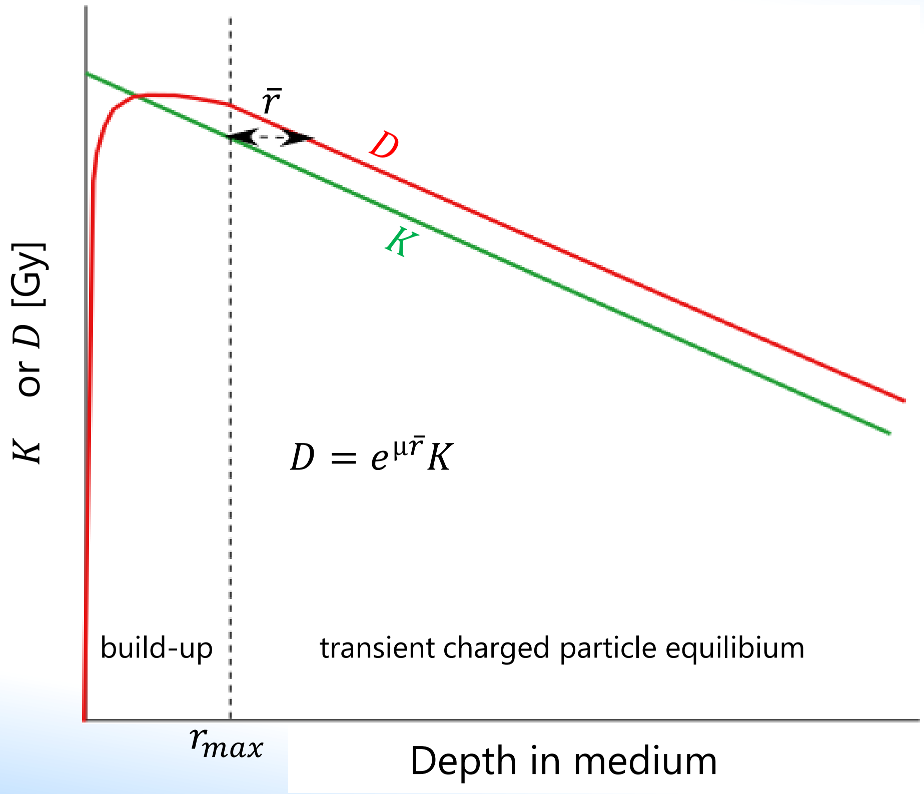
where $d\varepsilon$ is the mean energy imparted by ionizing radiation to matter in a volume element and dm is the mass of matter in the volume element

The energy can be averaged over any defined volume, the average dose being equal to the total energy imparted in the volume divided by the mass in the volume

The SI unit of absorbed dose is the joule per kilogram (J/kg), termed the gray (Gy)

The old unit of absorbed dose is rad: 1 rad= 0.01 Gy

Absorbed dose versus Kerma



Beam attenuation in water over the secondary electron or proton range [%]		
Primary energy [MeV]	Photons	Neutrons
0.1	0	0
1	1	0
10	7	1
30	15	4

Exposure

$$X = \frac{dQ}{dm}$$

where d*Q* is the absolute value of the total charge of ions produced in air when all the electrons liberated in air of mass d*m* are completely stopped in air

X is used to indicate the amount of ionization in air produced by x- or gamma-ray radiation

The SI unit of exposure is the coulomb per kilogram (C/kg)

The old unit of X is Röntgen: 1R = 0.000258 C/kg

Exposure

Exposure, X, in units of C kg^{-1}, is related to air kerma as follows:

$$X = \frac{K_a\,(1-g)e}{W}$$

where *W* is the average energy spent by an electron to produce an ion pair, *g* is the fraction of secondary charged particles that is lost to bremsstrahlung radiation production and *e* is the electronic charge

g=0 for X rays to 450 keV
g=0.004 for Co-60

Linear Energy Transfer (LET)

Linear Energy Transfer (LET)

$$L_{\Delta} = \left(\frac{dE}{dl}\right)_{\Delta}$$

where d*E* is the energy lost by a charged particle in traversing distance d*l* and Δ is an upper bound on the energy transferred in any single collision

The SI unit of LET is J/m or more commonly used keV/µm

Relative biological effect is related to LET

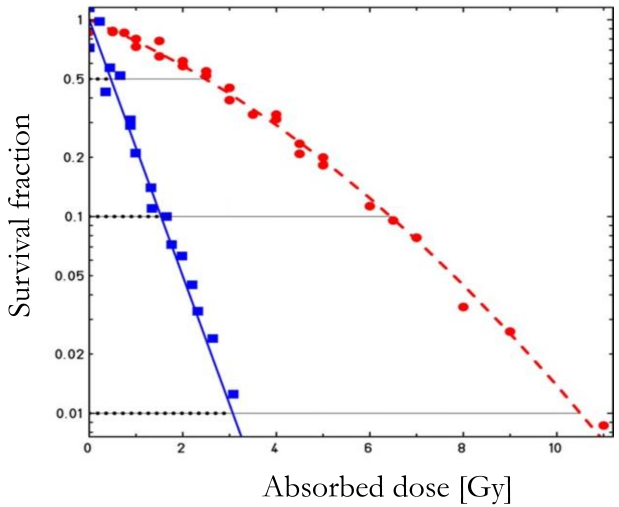
- LET is a measure of how, as a function of distance, energy is transferred from radiation to the exposed matter
- A high value of LET indicates that energy is deposited within a small distance
- LET is a measure of the relative biological impact of a given radiation type

- LET <10 keV/µm: low LET.
  - Examples: secondary electrons of gamma and X-rays, beta radiation
- LET >10 keV/µm: high LET
  - Examples: alpha radiation, heavier ions and secondary charged particles created by neutrons

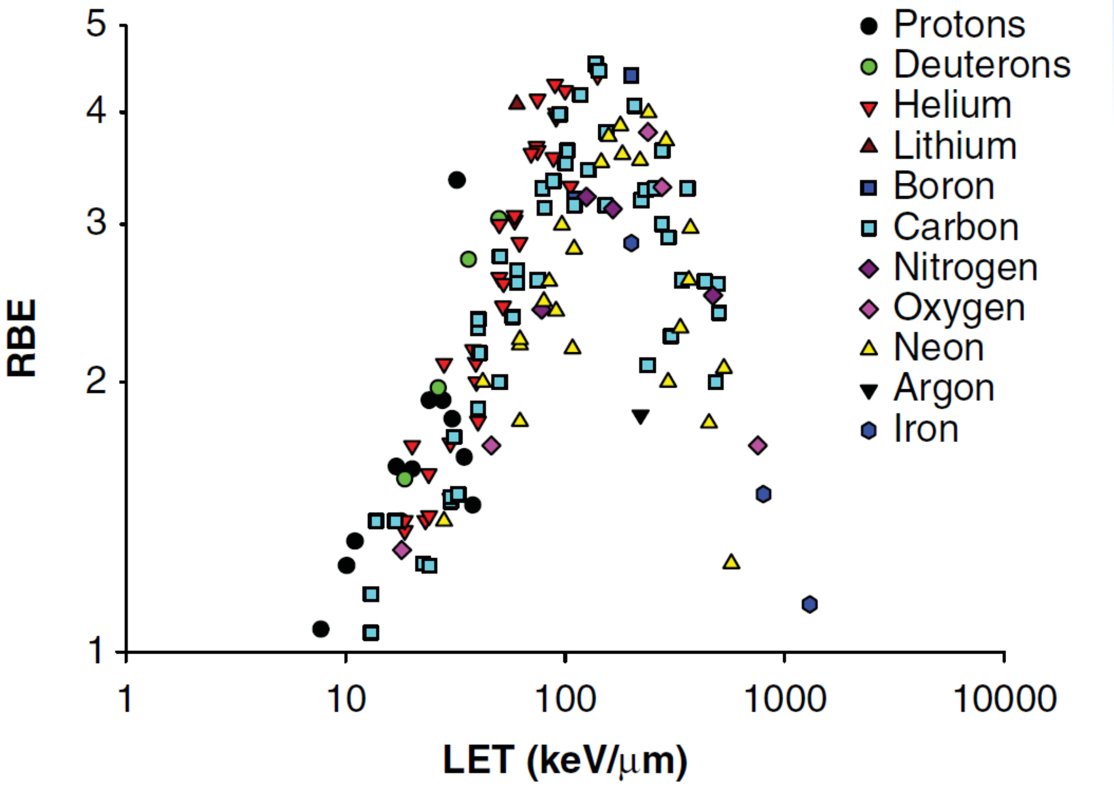
Relative biological effectiveness RBE

- Relative biological effectiveness (RBE)
- Ratio of the absorbed dose required to obtain a certain biological effect for the reference radiation type and energy (typically X-rays) over the absorbed dose required for the radiation type and energy of interest
- Depends on biological endpoint considered
- [dimensionless]

$$RBE = \frac{D_{reference\ radiation}}{D_{radiation\ under\ study}}$$



How damaging is each radiation type?



Protection Quantities

Biological effects of radiation

- Radiation induces damage in the cell, possibly leading to cell death or impossibility to reproduce
- If sufficient cells of an organ are dead: organ/tissue can stop to function normally
  - Tissue effects or deterministic effects
  - Has a certain dose threshold (threshold is dependent on organ/tissue)
  - More damage if more cells are affected
- Tissue effects are quantified by Organ absorbed Dose D_T or organ equivalent dose H_T

Biological effects of radiation

- Often cell damage is repaired
- If repair is not perfect: possible viable but changed cell
- Changed cells can lead to tumors or hereditary effects
  - Stochastic effects
  - Possibility of stochastic effects increase with increased level of radiation
  - No threshold dose
- Stochastic effects are quantified by effective dose E

Primary physical quantities can not be used directly for dose limitation

- Different body tissues have different biological sensitivities to the same radiation type and dose
  - Tissue weighting factor, w_T

- The same absorbed dose levels of different radiations (i.e. photons and neutrons) do not have the same level of biological effect
  - Radiation weighting factor, w_R

Organ equivalent dose H_T

- Equivalent dose in an organ or tissue, H_T
  - Used for limiting deterministic effects to body organs or tissues

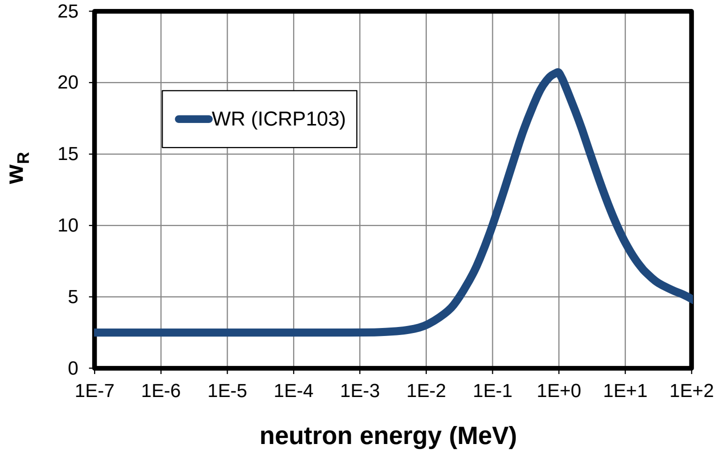
$$H_T = \sum_R w_R D_{T,R}$$

  - Radiation weighting factor, w_R : dimensionless factor by which the organ or tissue absorbed dose is multiplied to reflect the higher biological effectiveness of high-LET radiations compared with low-LET photon radiations
  - $D_{T,R}$ is the absorbed dose from radiation of type R averaged over the volume of tissue or organ T
  - The **radiation R** is given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within the body
  - The SI unit is J/kg, special name for the unit of equivalent dose is sievert (Sv)
  - The old unit of equivalent dose was rem, with 1 rem = 0.01 J kg–1 = 0.01 Sv

Organ equivalent dose H_T

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	$w_R = \begin{cases} 2.5 + 18.2 e^{-\{[\ln(E_n)]^2/6\}} & , E_n < 1\,\text{MeV} \\ 5.0 + 17.0 e^{-\{[\ln(2E_n)]^2/6\}} & , 1\,\text{MeV} \le E_n \le 50\,\text{MeV} \\ 2.5 + 3.25 e^{-\{[\ln(0.04E_n)]^2/6\}} & , E_n > 50\,\text{MeV} \end{cases}$

ICRP 103 (2007)



Effective Dose

- Effective dose, E
  - Estimates risk of health detriment from stochastic effects at low doses and allows for comparison of risks due to different exposure conditions

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

  - Tissue weighting factor, w_T, reflects different radiosensitivity of organs or tissues T
  - The SI unit is J/kg, special name for the unit of equivalent dose is sievert (Sv)
  - Legacy unit of equivalent dose was rem, with 1 rem = 0.01 J kg–1 = 0.01 Sv

Tissue Weighting Factor

Tissue	w_T	$\Sigma\ w_T$
Bone-marrow (red), colon, lung, stomach, breast, remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
		1.00

*Remainder tissues: Adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

ICRP 103 (2007)

Dosimetric quantities

- The use of effective dose is inappropriate for the assessment of tissue reactions
- In such situations it is necessary to estimate absorbed dose and to take into account the appropriate RBE (relative biological effectiveness) as the basis for any assessment of radiation effects
- RBE: is the ratio of biological effectiveness of one type of ionizing radiation relative to another, given the same amount of absorbed energy

History of Effective dose and Equivalent dose

- **ICRP 26 (1977 & statement 1978)**
  - Effective dose equivalent H_E (mainly for internal dosimetry)
    - Tissue weighting factors w_T
    - Quality factor $Q(L)$
- **ICRP 60 (1990)**
  - New concept of equivalent dose (for organs and tissues)
  - Effective dose E
    - Modified tissue weighting factors w_T
    - New concept of radiation weighting factors w_R
    - [Modified quality factors $Q(L)$]
- **ICRP 103 (2007)**
  - Modified tissue weighting factors w_T
  - Modified radiation weighting factors w_R

Dose Limits in Planned Exposure Situations

- Prevention of deterministic effects
- Reduction of stochastic effects to level deemed acceptable

Type of limit	Occupational	Public
Annual effective dose	20 mSv (avg. over 5 years[a])	1 mSv[b]
Annual equivalent dose to:		
Lens of the eye	20 mSv (avg. over 5 years[a])	15 mSv
Skin[c]	500 mSv	50 mSv
Hands and feet	500 mSv	—

a Not exceeding 50 mSv in any single year; additional restrictions apply to occupational exposure of pregnant women

b In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over 5 years does not exceed 1 mSv per year

c Averaged over 1 cm^2 area of skin regardless of the area exposed

Dose limits and risks

- Effective dose ~ risk for stochastic effects
  - Member of the public ~ 5.7 10^{-2} Sv^{-1}
  - Workers ~ 4.2 10^{-2} Sv^{-1}

- Examples:
  - Worker: every year reaching the dose limit of 20 mSv
    - After 50 years of work: 1 Sv = 4.2 % risk of stochastic effect
      - Including non-mortal tumours
  - 10/12 months 50 µSv
    - After 30 years: 0.06% risk

- ICRP does not give uncertainties on risk factors
  - They are large…

Operational Quantities

Operational Quantities

- Protection quantities, equivalent dose and effective dose, cannot be measured directly

- Other measurable quantities were introduced for the purpose of monitoring external radiation

- Operational quantities are designed to provide a failsafe estimate of the limiting quantities: substantial underestimates are avoided

- Detectors for area and individual monitoring are calibrated in terms of operational quantities

Overview of operational quantities

[sievert=Sv]	Ambient dosimeters	Personal dosimeters
Effective dose	Ambient dose equivalent H*(10)	Personal dose equivalent $H_p(10)$
Organ equivalent dose		
- Eye lens	Directional ambient dose equivalent $H'(3,\Omega)$	Personal dose equivalent $H_p(3)$
- Skin, hands, feet	Directional ambient dose equivalent $H'(0.07,\Omega)$	Personal dose equivalent $H_p(0.07)$

Operational Quantities (ICRU)

- Dose equivalent, H, is the product of Q and D at a point in tissue, where D is the absorbed dose and Q is the quality factor at that point $H = Q.D$
- 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 a radius opposing the direction of the aligned field: $H^*(d)$
- Directional dose equivalent, $H'(d, \Omega)$ 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 specific direction Ω: $H'(d, \Omega)$
- Personal dose equivalent $H_p(d)$ at a point in a radiation field is the dose equivalent in soft tissue at an appropriate depth d, below a specified point on the body: $H_p(d)$

- Unit: J/kg^{-1}, special name sievert (Sv)

Operational quantities

- For the assessment of effective dose a depth *d* = 10 mm is recommended, and for assessing equivalent dose to the skin, and to the hands and feet, a depth *d* = 0.07 mm. For eye-lens dosimetry, a depth of 3 mm is recommended

- The value of $H_p(d)$ depends on the position of measurement on the body
- A water filled slab phantom, 30cm x 30cm x 15cm is recommended for calibrating dosimeters used to measure exposure to the whole body
- Conversion coefficients for calibrating dosimeters for whole body monitoring have been calculated using a slab of ICRU muscle substitute, 30cm x 30cm x 15cm, $H_{p,slab}(d)$

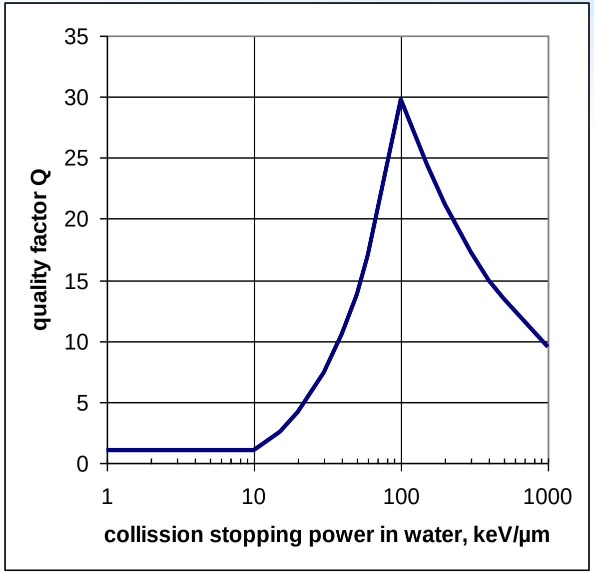
Quality factor defined in ICRP 60/103

Table A-1. Specified Q–L relationships

Unrestricted linear energy transfer, L in water (keV μm^{-1})	$Q(L)$[1]
< 10	1
10–100	$0.32L-2.2$
> 100	$300/\sqrt{L}$

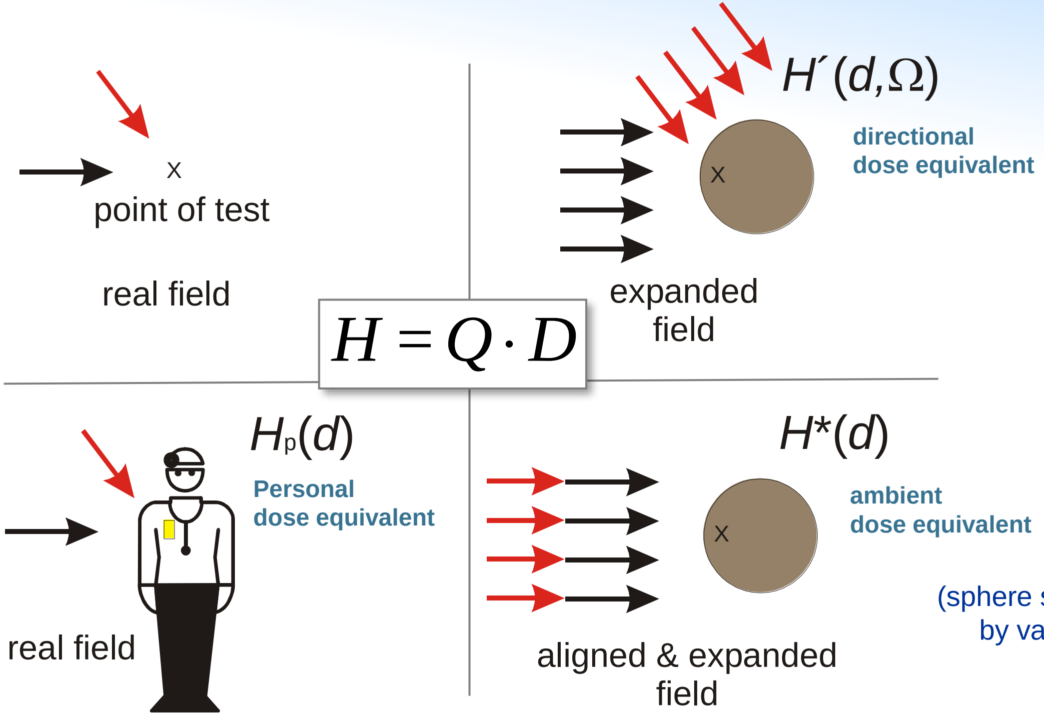
[1] With L expressed in keV μm^{-1}.

ICRP 103 (2007) & 60 (1990)



$$H = Q \cdot D$$

Operational quantities



(sphere surrounded
by vacuum?)

ICRU sphere:
diameter: 30 cm,
density: 1 g cm-3

Composition:
76,2 % oxygen,
11,1 % carbon,
10,1 % hydrogen
2,6 % nitrogen

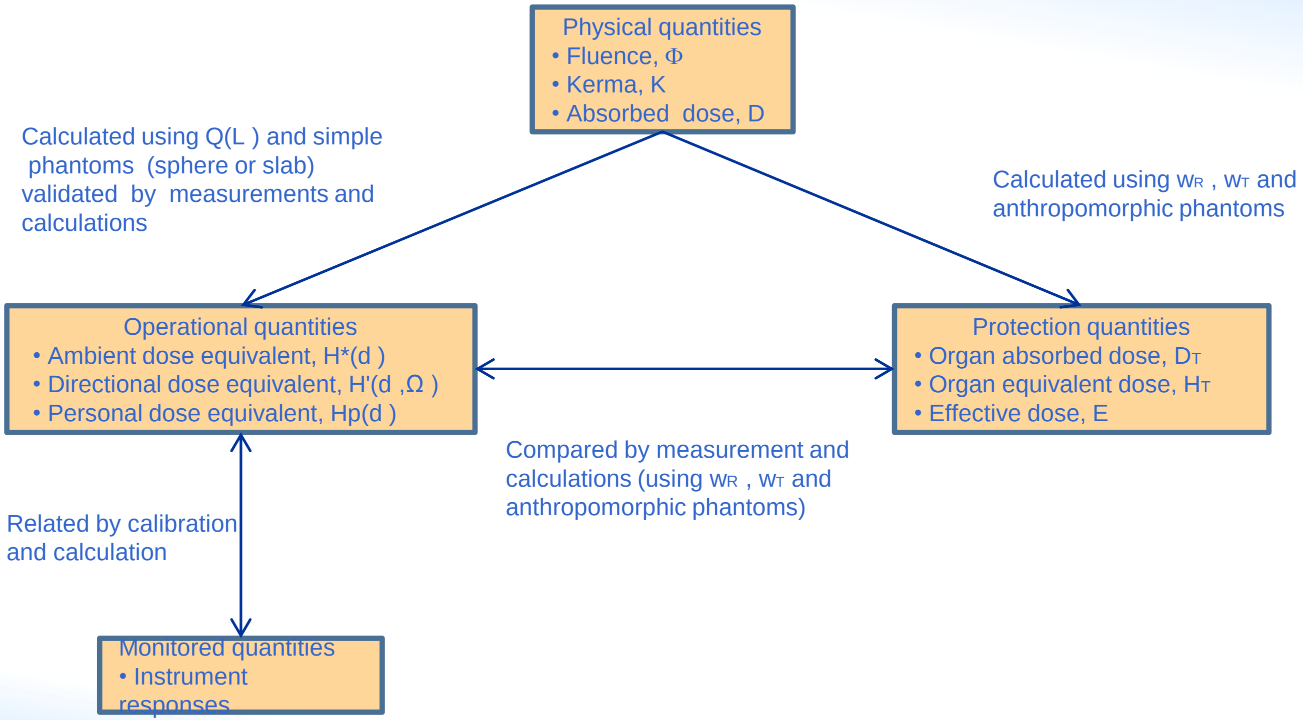
•Schematic example of expanded and aligned radiation fields used in the definition of the operational quantities $H^*(d)$ and $H'(d, \Omega)$, defined in the ICRU-sphere. The quantity $H_p(d)$ is defined in the real field in a point in the human body wearing a dosimeter

History of the operational quantities

- **ICRP 39 (1985)**
  - Ambient dose equivalent $H^*(d)$
  - Directional dose equivalent $H'(d)$
  - Individual dose equivalent penetration $H_p(d)$
  - Individual dose equivalent superficial $H_s(d)$
- **ICRP 43 (1988)**
  - d= 0,07 mm and 10 mm
  - Calibration phantom for $H_p(d)$: ICRU sphere
- **ICRP 47 (1992)**
  - Personal dose equivalent penetration $H_p(d)$
  - Calibration phantom for $H_p(d)$:
    - Slab (PMMA, Water)
- **ICRP 51 (1993)**
- d= 3 mm for eye lens

Conversion Coefficients

Dosimetric quantities



Dose Conversion Coefficients

Energy dependent dose conversion coefficients are used to establish the relationship between the Primary Physical Quantities, and the Protection Quantities and Operational Quantities

For photons, the reference Primary Physical Quantity is Kerma, free in air, or "Air Kerma", K_a

The photon conversion coefficients have units of Sv/Gy

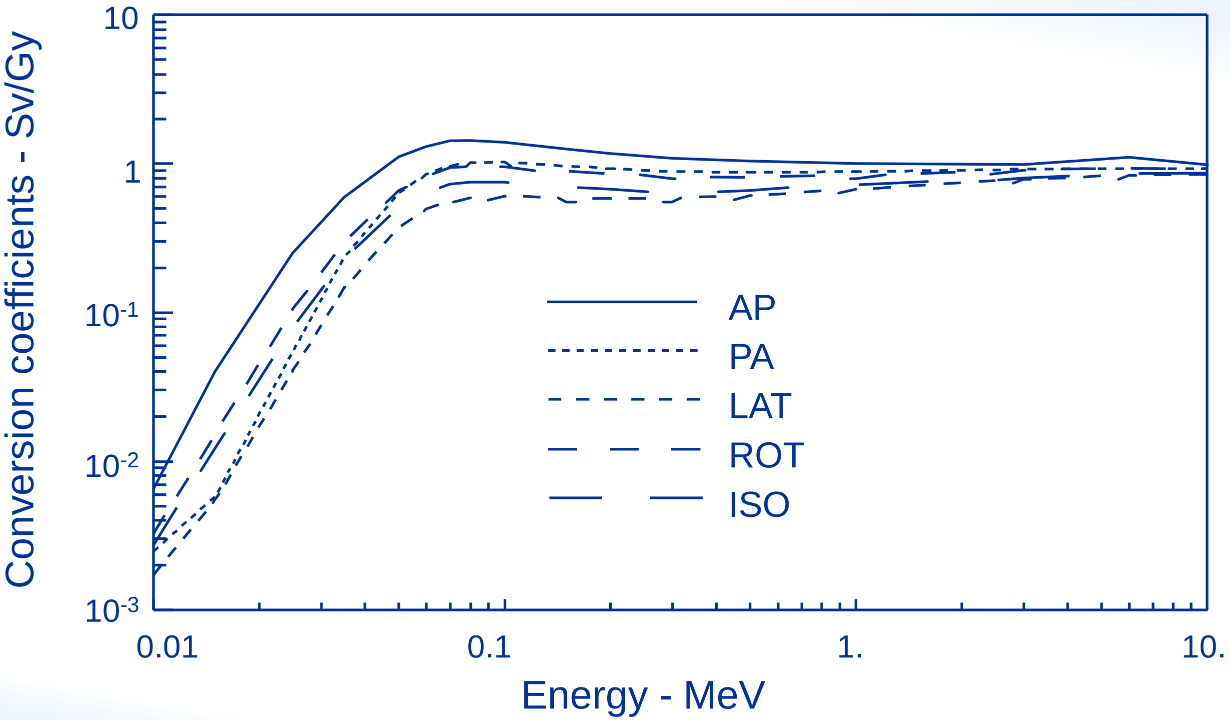
For neutrons, the reference Primary Physical Quantity is Fluence

The neutron conversion coefficients have units of Sv cm^2

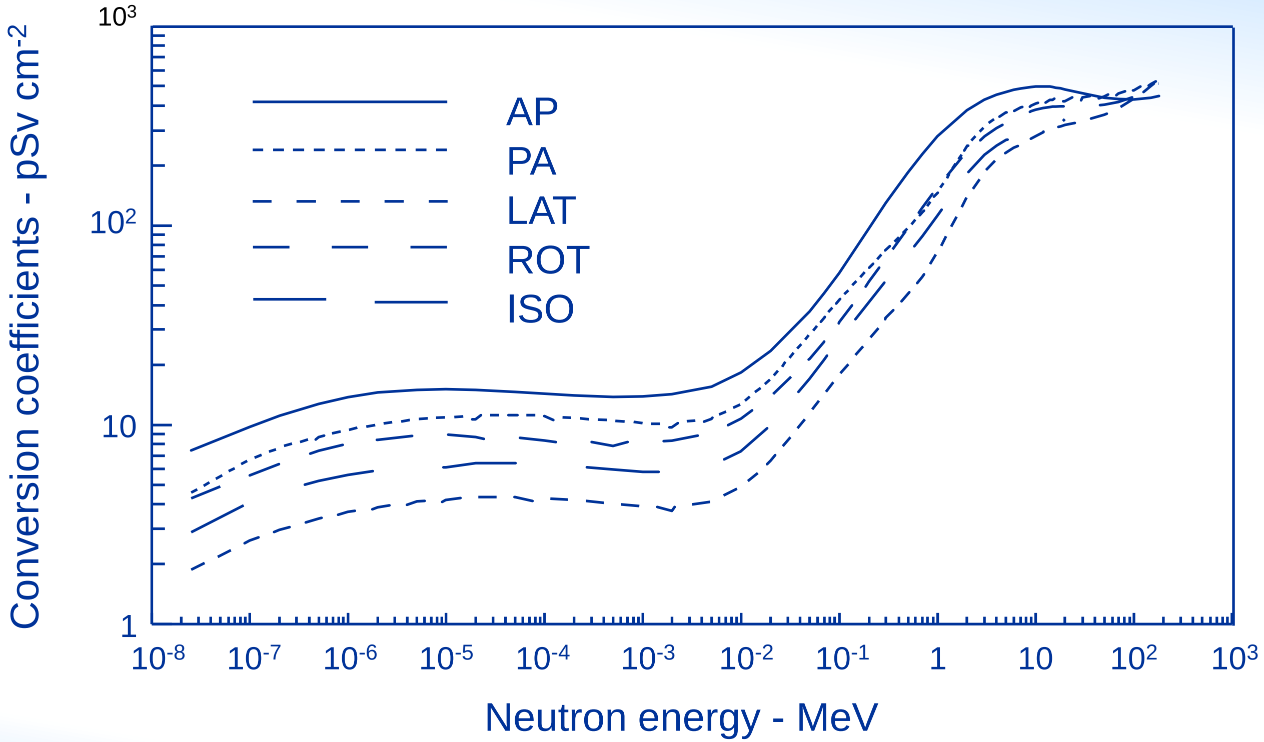
Conversion coefficients

- **ICRU 43 (1988)**
  - based on effective dose equivalent H_E
- **ICRU 47 (1992)**
  - coefficients for operational quantities
- **ICRP 74 (1996) & ICRU 57 (1998)**
  - Based on effective dose (ICRP 60 / 1990)
  - Based mostly on ADAM, EVA, and MIRD-5 phantoms.
  - Values for photons, neutrons, electrons
  - coefficients for operational and protection quantities
- **ICRP 116 (2010) & ICRU**
  - Based on effective dose (ICRP 103 / 2007)
  - Based on ICRP 110 phantoms
  - Values for photons, neutrons, electrons, positrons, pions, muons, helium ions
  - Extended energy range

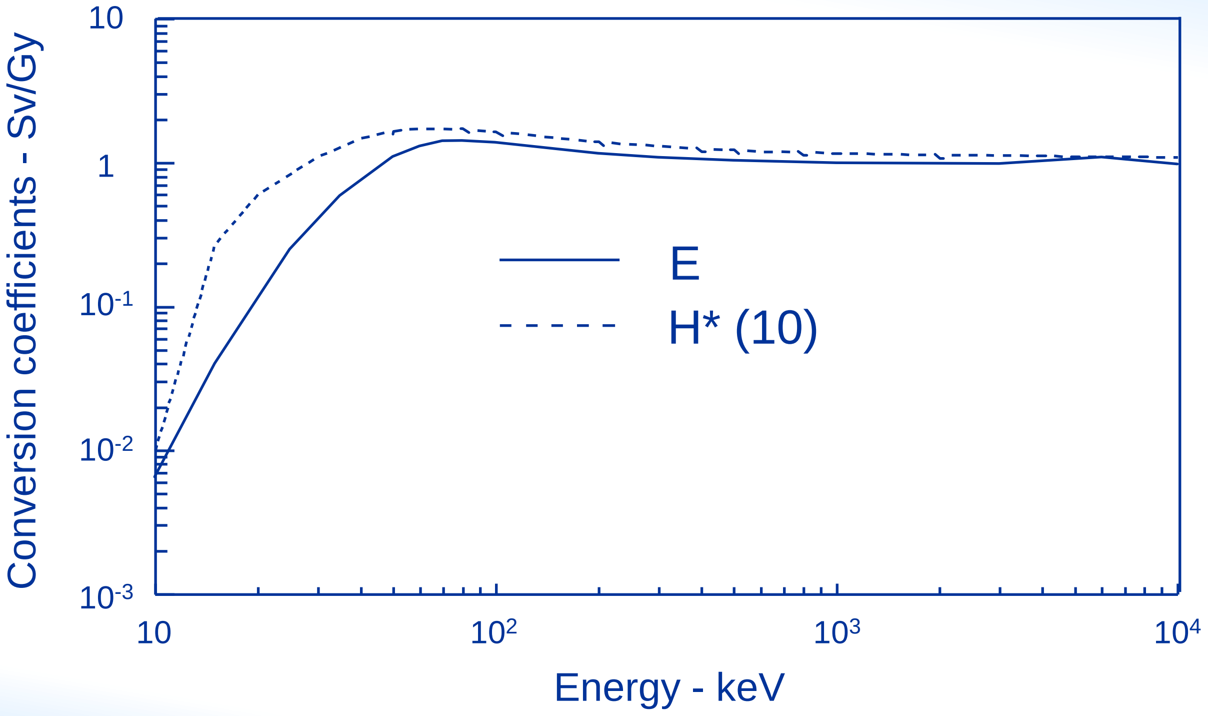
Photon dose conversion coefficients for Effective Dose



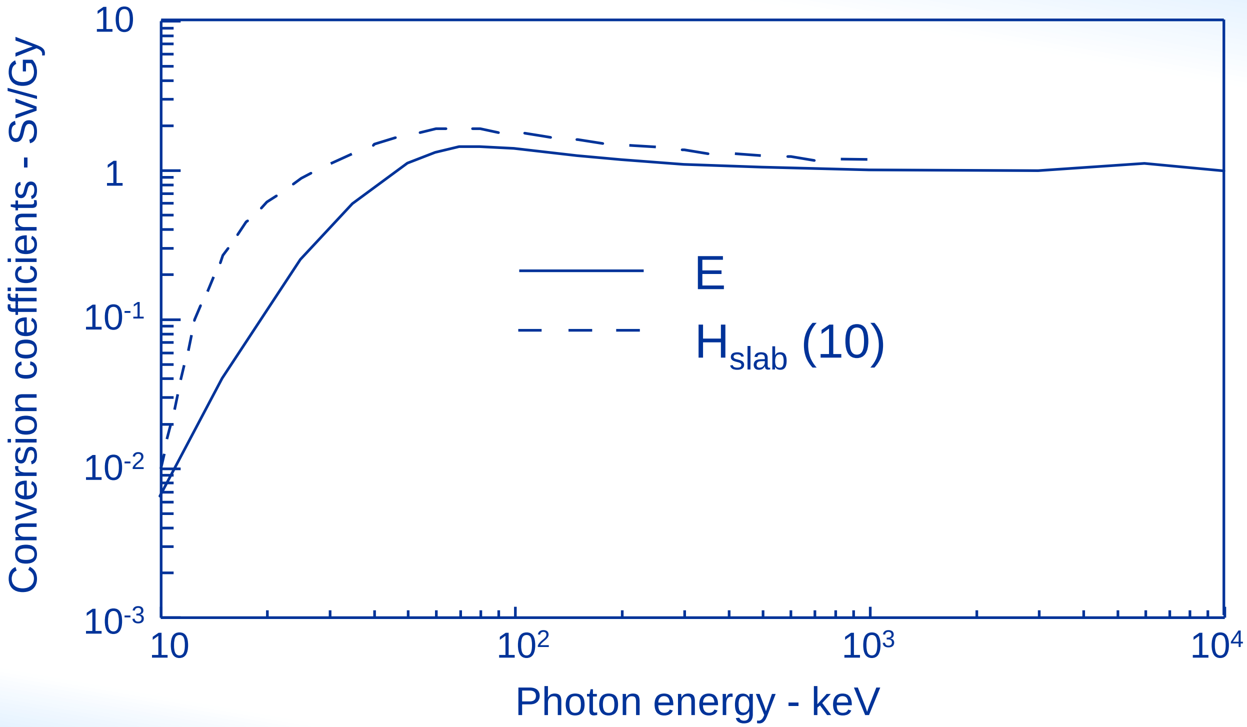
Neutron dose conversion coefficients for Effective Dose



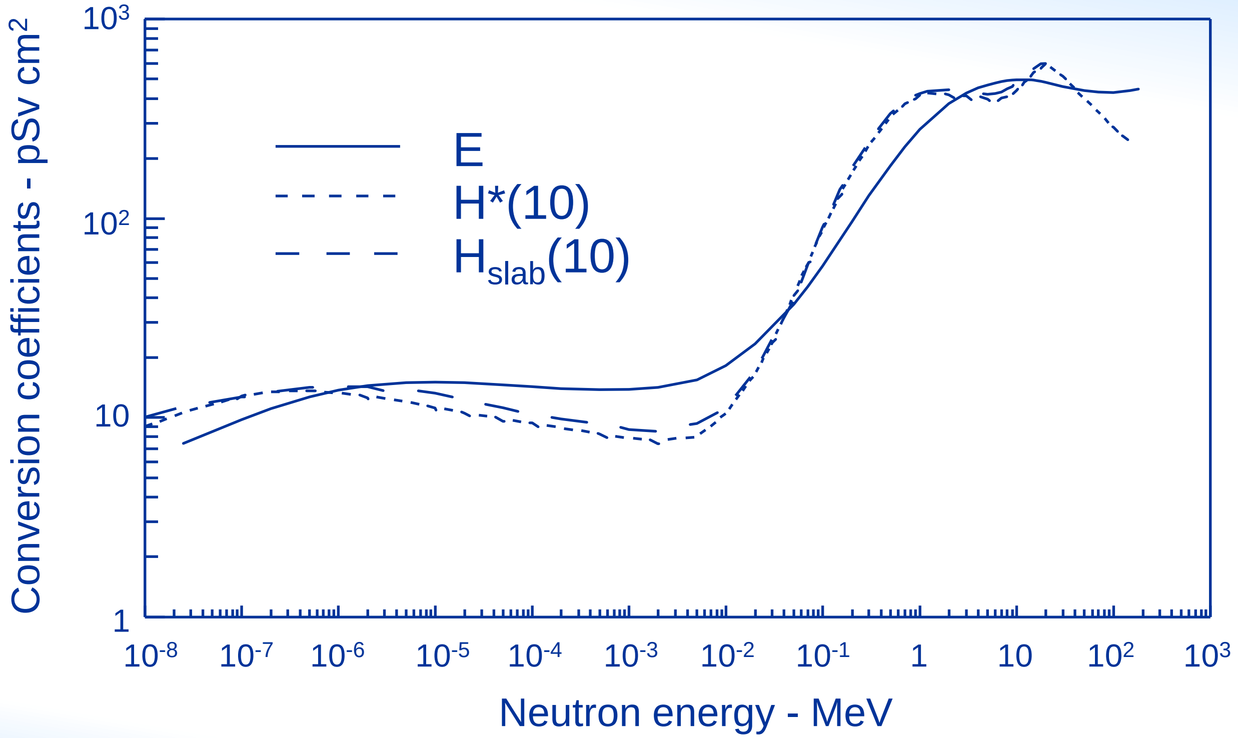
Photon dose conversion coefficients for E and H*(10)



Photon dose conversion coefficients for E and Hslab



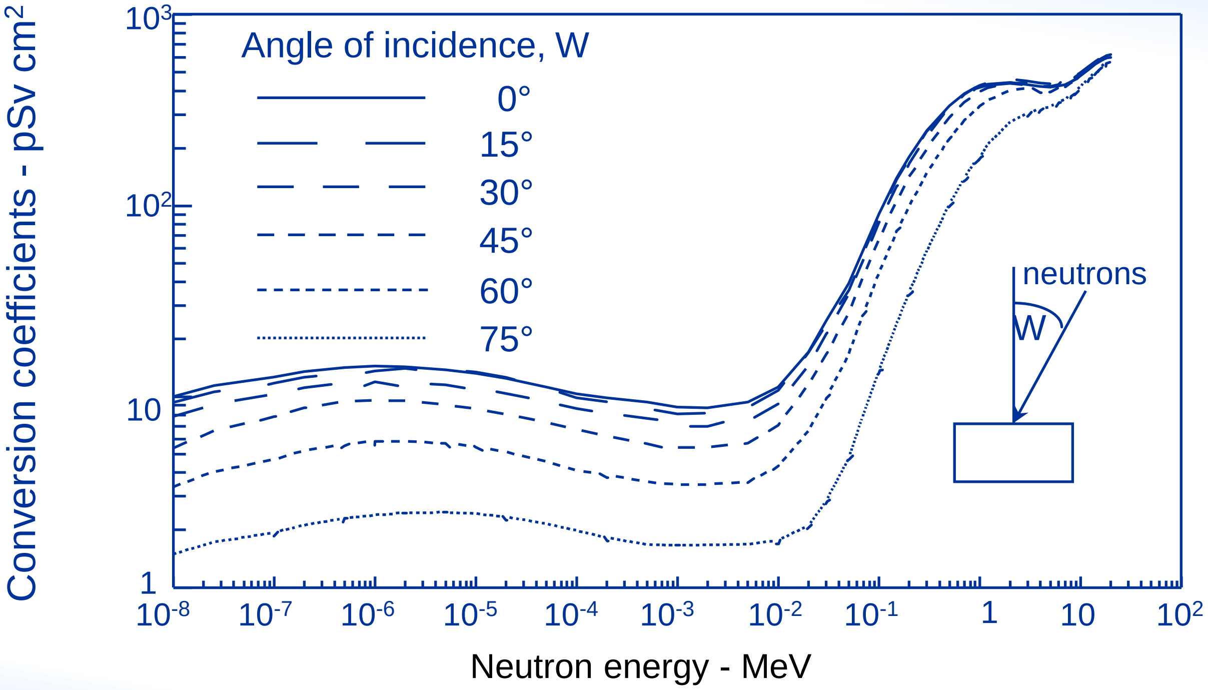
Neutron dose conversion coefficients



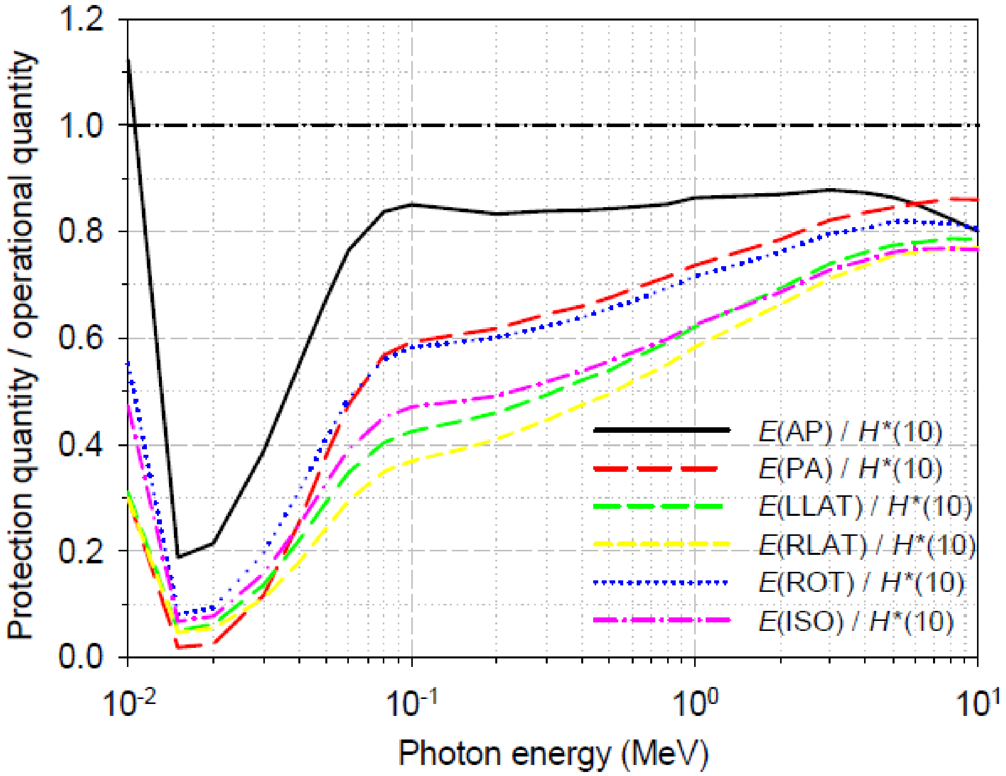
Conversion Coefficients from air kerma to $H_p(10)$ in an ICRU slab and angular dependence factors (photons)

Photon energy (MeV)	$H_p(10,0^o)/K_a$ (Sv/Gy)	Ratio $H_p(10,\alpha)/H_p(10,0^o)$ for angles α					
		0º	15º	30º	45º	60º	75º
0.010	0.009	1.000	0.889	0.556	0.222	0.000	0.000
0.0125	0.098	1.000	0.929	0.704	0.388	0.102	0.000
0.015	0.264	1.000	0.966	0.822	0.576	0.261	0.030
0.0175	0.445	1.000	0.971	0.879	0.701	0.416	0.092
0.020	0.611	1.000	0.982	0.913	0.763	0.520	0.167
0.025	0.883	1.000	0.980	0.937	0.832	0.650	0.319
0.030	1.112	1.000	0.984	0.950	0.868	0.716	0.411
0.040	1.490	1.000	0.986	0.959	0.894	0.760	0.494
0.050	1.766	1.000	0.988	0.963	0.891	0.779	0.526
0.060	1.892	1.000	0.988	0.969	0.911	0.793	0.561
0.080	1.903	1.000	0.997	0.970	0.919	0.809	0.594
0.100	1.811	1.000	0.992	0.972	0.927	0.834	0.612
0.125	1.696	1.000	0.998	0.980	0.938	0.857	0.647
0.150	1.607	1.000	0.997	0.984	0.947	0.871	0.677
0.200	1.492	1.000	0.997	0.991	0.959	0.900	0.724
0.300	1.369	1.000	1.000	0.996	0.984	0.931	0.771
0.400	1.300	1.000	1.004	1.001	0.993	0.955	0.814
0.500	1.256	1.000	1.005	1.002	1.001	0.968	0.846
0.600	1.226	1.000	1.005	1.004	1.003	0.975	0.868
0.800	1.190	1.000	1.001	1.003	1.007	0.987	0.892
1.0	1.167	1.000	1.000	0.996	1.009	0.990	0.910
1.5	1.139	1.000	1.002	1.003	1.006	0.997	0.934
3.0	1.117	1.000	1.005	1.010	0.998	0.998	0.958
6.0	1.109	1.000	1.003	1.003	0.992	0.997	0.995
10.0	1.111	1.000	0.998	0.995	0.989	0.992	0.966

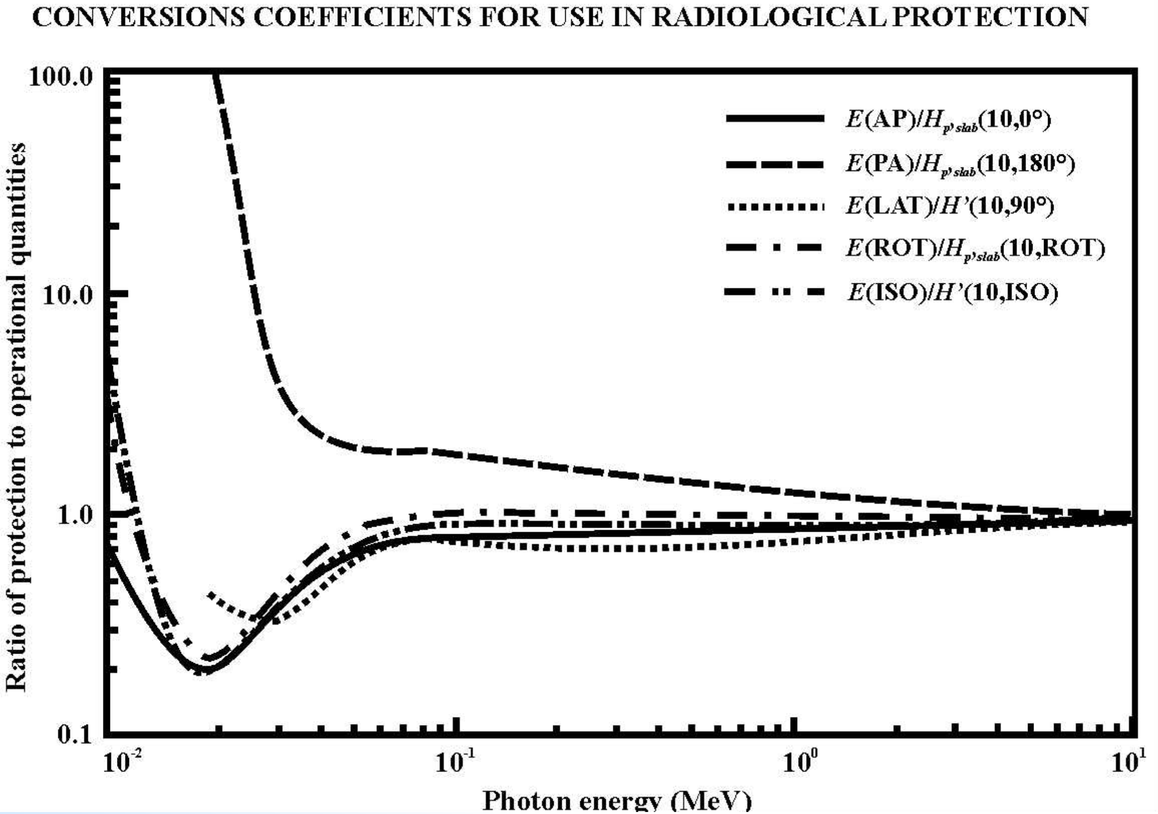
Neutron $H_p(10)$ conversion coefficients depend on angle



H*(10) > E in order to be conservative and safe



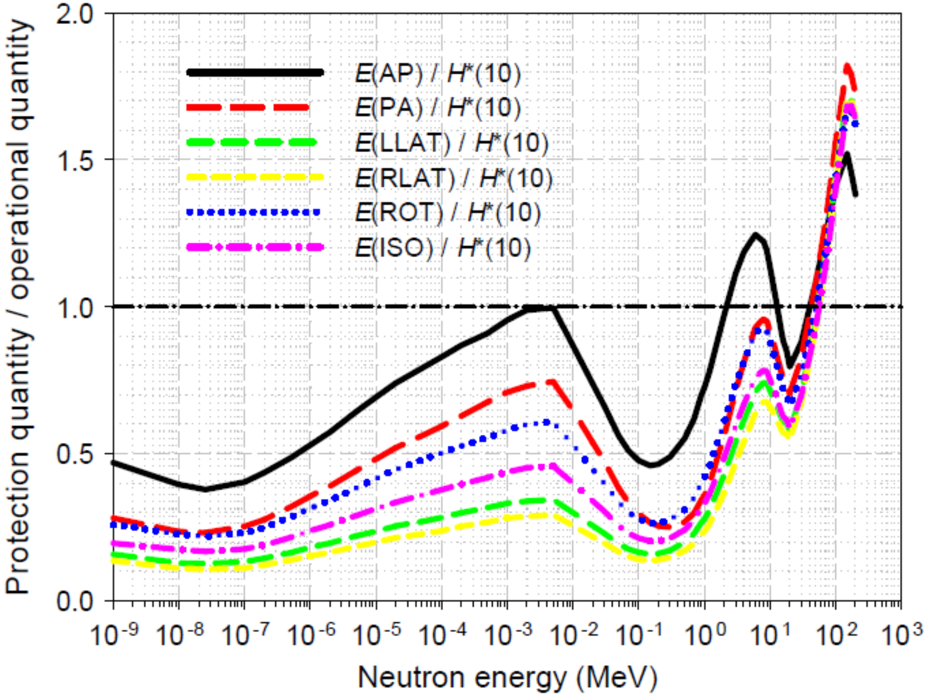
$H_p(10)$> E in order to be conservative and safe



$H^*(10)$ as an indicator of E in AP geometry

IAEA

ICRP Publication 116



Example of the calculation of effective dose

EXERCISE

Let's assume an exposure to an absorbed dose of 1 Gy Gamma and 1 Gy thermal neutron in the lungs and in the thyroid.

Compare the effective doses

Gegevens :

$D_{T, R} = 1$ Gy

$w_{gamma} = 1$

$w_{th.n} = 2.5$

$w_{lungs} = 0.12$

$w_{thyroid} = 0.04$

EXERCISE

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

$$H_T^{gamma} = 1 * 1 = 1 \text{ Sv}$$

$$H_T^{th.n} = 2.5 * 1 = 2.5 \text{ Sv}$$

EXERCISE

IAEA

$$E = w_T \cdot H_T$$

$$E_{lungs}^{gamma} = 1 * 0.12 = 0.12\ Sv$$

$$E_{lungs}^{th\ n} = 2.5 * 0.12 = 0.6\ Sv$$

$$E_{thyroid}^{gamma} = 1 * 0.04 = 0.04\ Sv$$

$$E_{thyroid}^{th.n.} = 2.5 * 0.04 = 0.1\ Sv$$

$$E_{total} = 0.12 + 0.04 + 0.6 + 0.1 = 0.86\ Sv$$

New operational quantities

Timeline for new operational quantities

- New ICRU report on new operational quantities
- Wide consultation round
- Adopted by ICRP
- Common publication
- Timeline
  - To be adapted in new general ICRP recommendations
  - To be adapted by BSS
  - To be adapted by national legislations
  - Transition period: Time for user/manufacturers to adapt
- Into practice at 2030 (?)

Conceptual Shortcomings of the present quantities

- Dose at specific depth (*d* = 10 mm) cannot reproduce complexity of body reflected in effective dose *E*
- Use of different phantoms for
  - protection quantities
  - operational quantities
- Use of dose equivalent (Sv) to estimate deterministic effects (lens of eye, local skin)
- System difficult to understand
- Numerical values incoherent

Shortcomings of ICRP 74 / ICRU 57 Conversion coefficients

- No conversion coefficients for very high energies
- Only photons, neutrons, electrons considered
- Overestimate of photon effective dose at low energies (E_p< 30 keV)
- Overestimate of legally adopted photon dose conversion coefficients (calculated in kerma approximation
  - for skin from E_p > 0.07 MeV
  - for eye lens from E_p > 0.2 MeV
  - for effective dose (whole body) for E_p > 3 MeV
- Correctly calculated photon values with full electron transport lead actually to underestimates at higher energies

New operational quantities: change of Paradigm

- Define the operational quantities as the product of field quantity (here fluence) and a conversion coefficient

$$H = h_{\varphi} \cdot \Phi_{E_\mathrm{p}}$$

- Φ_{E_p} is the unperturbed external fluence spectrum
- Derive conversion coefficient $h(E_p)$ from the same phantoms as the protection quantities by:

$$h(E_p) = E / \Phi_{E_\mathrm{p}} \text{ or } h(E_p) = D / \Phi_{E_\mathrm{p}}$$

Kerma in air can be used alternatively to fluence

Whole-body dosimetry

- Personal dose:

$$H_p = h_p(E_p, \Omega) \cdot \Phi(E_p)$$

- Calculation of conversion coefficients:

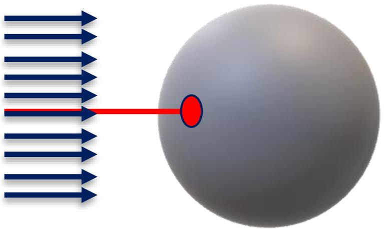
$$h_p(E_p, \phi) = E(E_p, \phi) / \Phi(E_p)$$

- Consequence
  - Numerical coherence between *E* and *H*
  - automatically good approximation

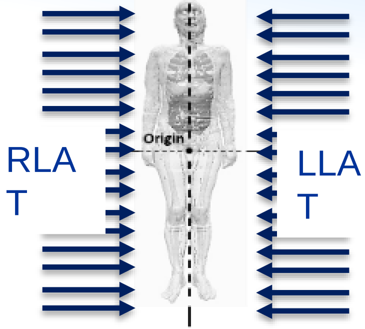
$$H_p(E_p, 0^o) = E(E_p, \mathrm{AP})$$
$$H_p(E_p, 180^o) = E(E_p, \mathrm{PA})$$

Area Monitoring

*H**(10) – Ambient Dose Equivalent



*H** - Ambient Dose



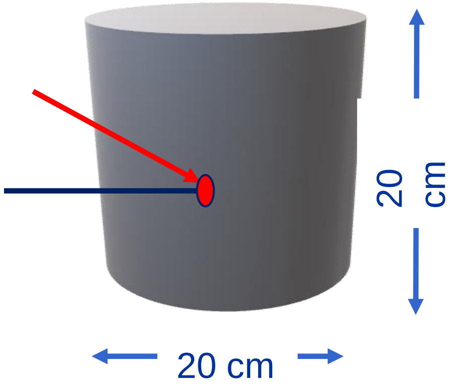
Maximum of Effective Dose Under different directions

$$H^* = h_{E_{\max}} \cdot \Phi$$

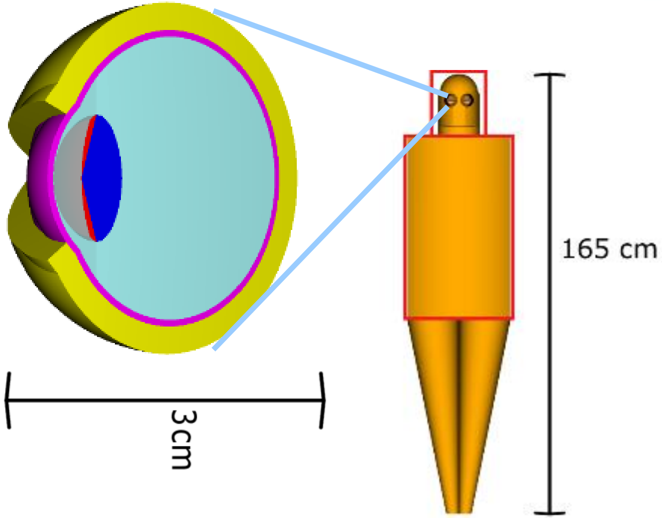
$$h_{E_{\max}}(E_p) = E_{\max}(E_p) / \Phi(E_p)$$

Eye lens monitoring

$H_p(3)$



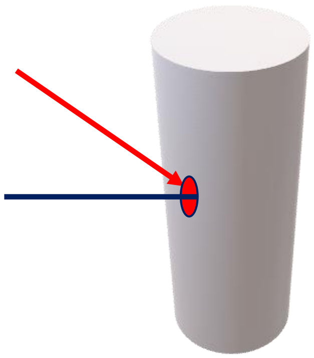
$D_{\text{eye lens}}$



Absorbed dose in eye lens in stylized Behrens-Dietze eye phantom

Monitoring the Extremities

$H_p(0.07)$

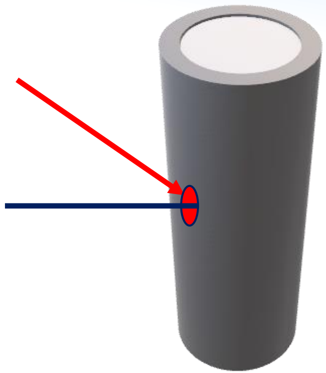


Dose equivalent in 0.07 mm in

- Finger: 1.9 cm * 30 cm
- Wrist: 7.3 cm * 30 cm

ICRU tissue ρ = 1.0 g/cm^3

$D_{local\ skin}$

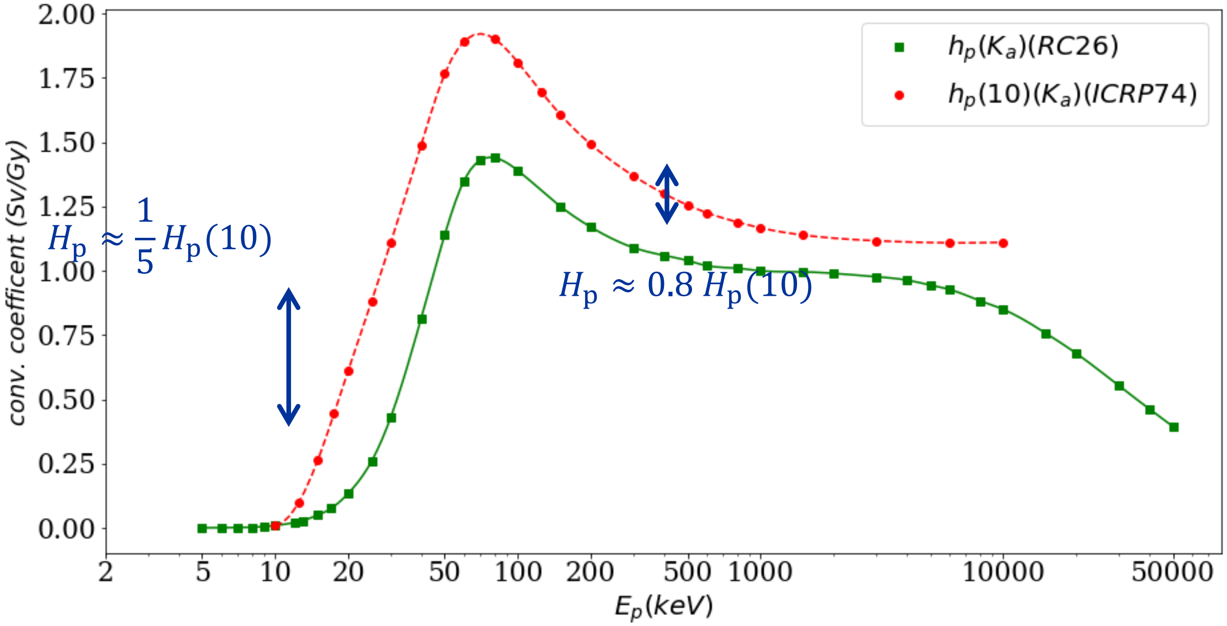


Absorbed dose between 0.05 and 0.1 mm in

- Finger: 1.9 cm * 30 cm
- Wrist: 7.3 cm * 30 cm

ICRU tissue ρ = 1.11 g/cm^3 with 0.2 cm ICRP skin

Conversion coefficients from kerma to new operational quantity



Are we loosing conservatism ?

- Personal dosimetry is the applied science to approximate *effective dose E* by measurement
- Good radiation protection practice makes use of optimization and constraints to keep the exposure of personnel ALARA.
- The right place for conservatism is in the procedures of the radiation protection program, not in the definition of the quantities.

Pro / Contra new Quantities

- Simplified and numerically coherent system
- No more ICRU sphere – is this a big loss ?
- Better approximation of *E* for low energy photons
- Extension to high energies
- Calibration procedures remain unchanged
- Response changes to personal dosimeters,
- New dosimeter and algorithm designs, investment