PAUL SCHERRER INSTITUT

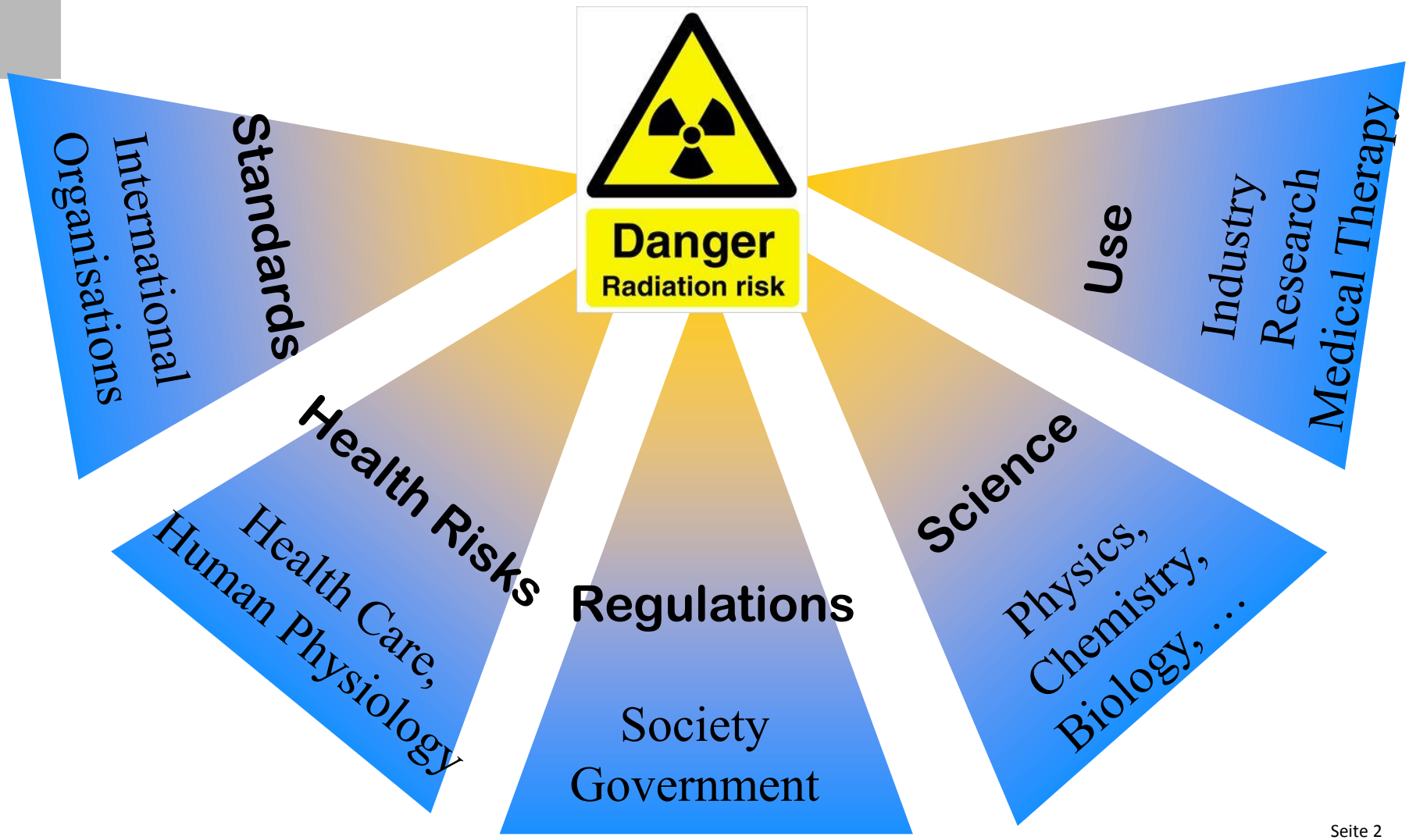
PSI

Frank Assenmacher :: Dosimetry :: Paul Scherrer Institute

Radiation Protection Dosimetry

European Summer School 2017, Université Strasbourg, 25. August 2017

Radiation Protection Dosimetry is multidisciplinary

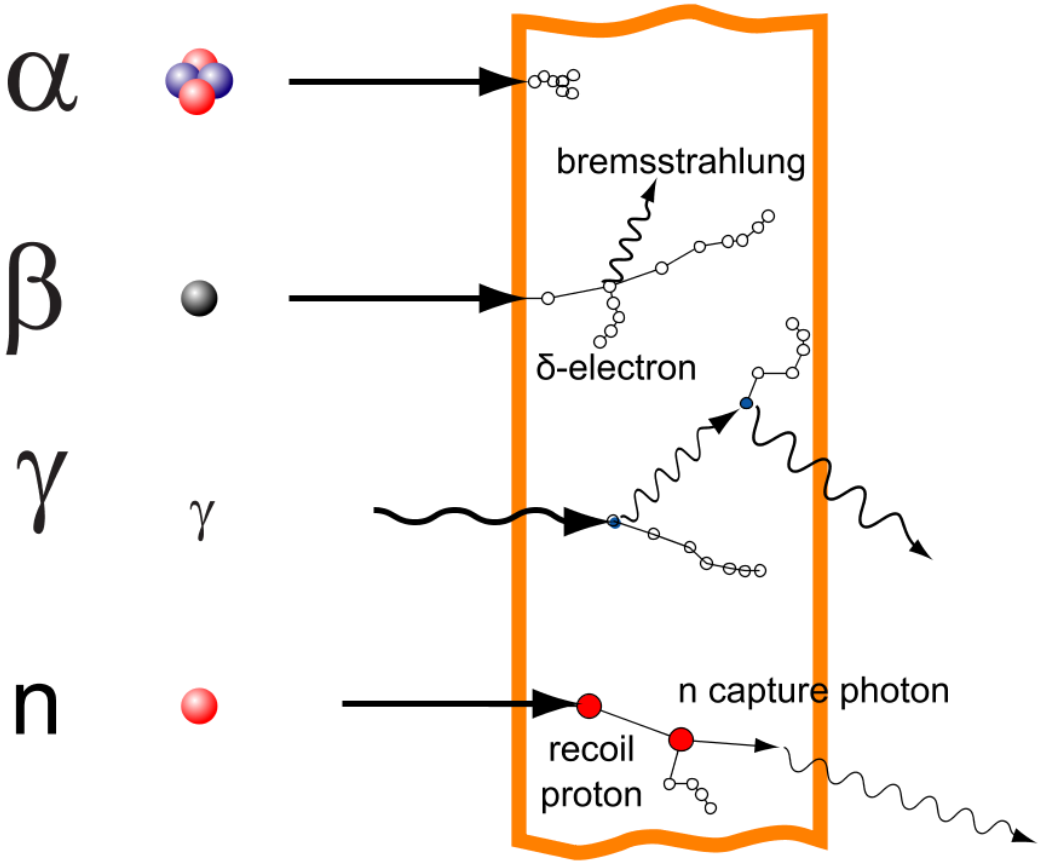


Radiation Protection Dosimetry

- **Ionizing radiation: particles, interactions, physical effects**
- **Health risks and biological effects**
- **Dosimetry concepts, units and quantities**

This lecture puts emphasis on essential ideas, concepts and knowledge on radiation protection dosimetry in the human body.
Dosimetry of incorporated radionuclides is omitted as the methods are quite different, but nevertheless challenging and interesting as well.

Ionizing Radiation - Particles



Baryons:
- Alpha
- Proton
- Neutron

Leptons (beta's):
- Electron
- Positron

Photons (gamma's):
- X-ray
- Gamma

Mesons:
- Pion
- …

Ionizing Radiation

Radiation is the transport of:

- kinetic energy by particles with mass
- electromagnetic energy by photons
- (neutrons leading to activation of matter)

Ionization is the release or detachment of electrons from atoms or molecules.

Electrically charged particles (electrons, positrons, protons, alpha, ions) are directly ionizing. Due to their charge, they interact many times by Coulomb forces, slow down by partial kinetic energy transfer or bremsstrahlung (beta), have a short range in dense material, and produce a dense track of ionizations.

Uncharged particles (neutrons) and photons are considered indirectly ionizing. Charged particles need to be released first for further ionizations. Uncharged particles interact sparsely even in dense material, and do not produce a track of ionizations by themselves but disconnected interactions. The secondary charged particles then produce ionization tracks.

Charged Particles

Protons, alphas and heavier ions

- Interact with matter mainly by collisions with atomic nuclei and electrons
- Energy loss due to bremsstrahlung is negligible
- The average energy loss by collisions is described by the Bethe-Bloch-formula
- Very short range in matter compared to lighter charged particle types with same energy. E.g. alpha with 5 MeV: 70µm, proton with 70 MeV: 40 mm

Electrons, positrons

- Interact with matter by collisions with charged particles
- Energy loss due to bremsstrahlung is significant
- Positrons annihilate when at rest, and 2 x 511 keV photons are emitted

Delta-electrons are high-energy secondary electrons which are detached with a significant portion of the energy of the initial particle, and start a new track of ionizations.

Photons

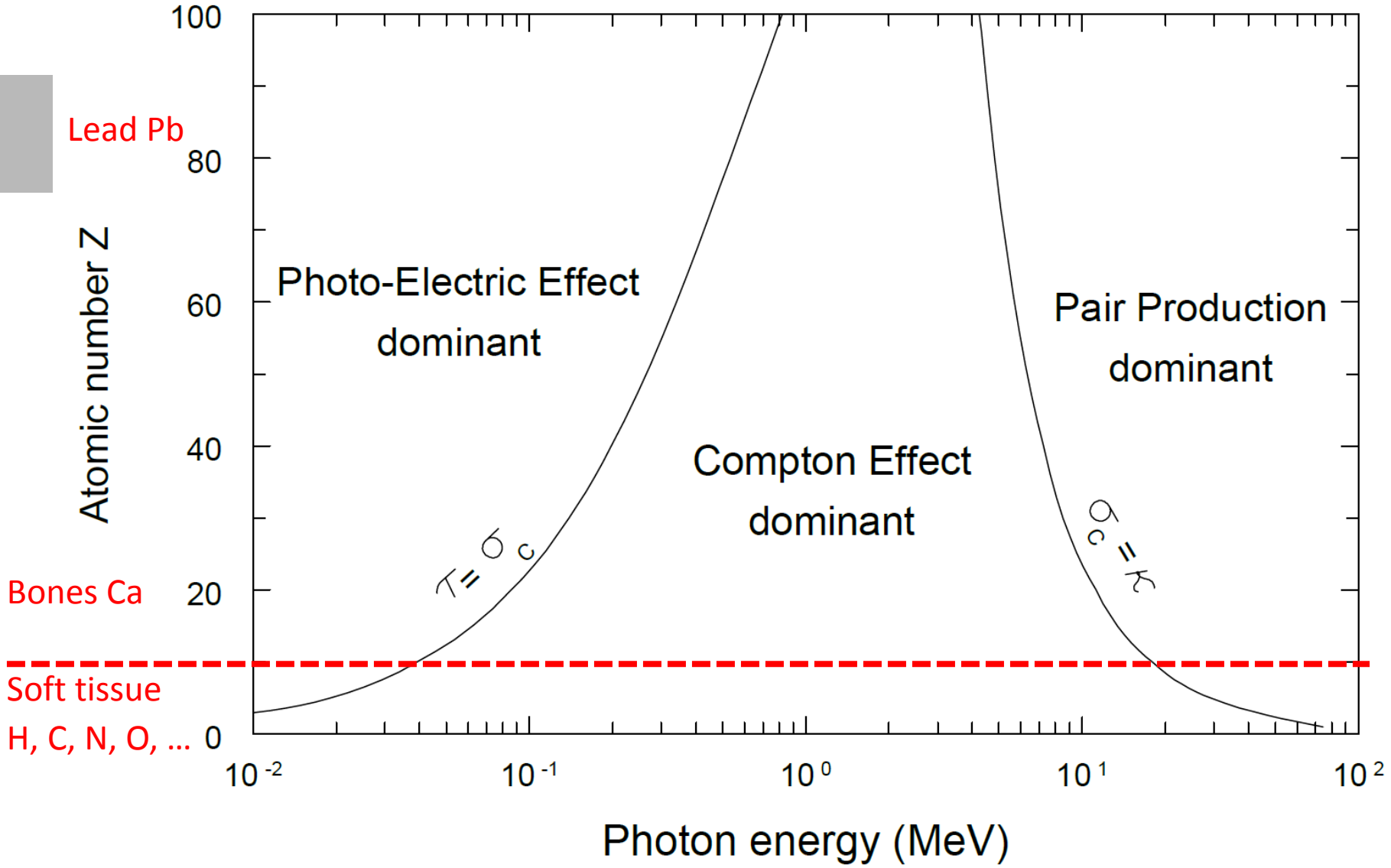
Photons:

- No rest mass, neutral, energy quantum of an electromagnetic field
- Always absorbed completely, but new photons may be produced with lower energy
- Photon radiation is attenuated:
  $I(x) = I_0 \cdot e^{-\mu x}$ with mass attentuation coefficient μ and initial fluence I_0

Main interactions of photons with matter:

- Elastic Rayleigh scattering: no energy loss, but change in direction
- **Compton effect:** emission of a new photon of lower energy and detachment of an electron. Dominant interaction of X-ray photons. Could be interpreted as "*track of ionizations by Compton-interactions*"
- **Photoelectric effect:** detachment of an electron. Electronic binding energies in soft tissue are usually below 3.7 keV (Ka1-Line of Ca)
- **Pair production:** production of a positron and an electron, followed by annihilation of the positron with an electron to 2x 511 keV photons
- Photonuclear interactions: high energy gammas may interact with atomic nuclei, knocking out fragments

Dominant Photon Interactions in various Media



Neutrons

- Long distance between interactions even in dense material
- Elastic/inelastic scattering without/with excitation of atomic nuclei
- Slowing down by partial kinetic energy transfer at each interaction
- Slow neutrons get captured by any kind of nuclei quite efficiently, often producing excited atomic nuclei
- Decay of the free neutron with half-life of 660 sec is negligible and hard to observe
- Fast neutrons of 20 MeV thermalize within milliseconds down to keV energy range
- Neutrons with kinetic energy > 100 keV can produce recoil protons
- Maximum kinetic energy transfer in collisions with protons, because of same mass

Neutrons	Kinetic Energy	Speed [km/s]	Dominant interaction
Thermal	< 0.5 eV	< 10	Capture
Epithermal	< 200 keV	< 200	Resonances
Fast	< 20 MeV	< 62’000	Elastic and inelastic scattering
Relativistic	> 20 MeV	> 62’000	Fission

Ionizing Radiation – Interactions

Interactions with energy transfer to secondary particles:

- Collisions and ionization
- Delta-electrons (high energy electrons)
- Recoil protons
- Nuclear excitations mainly by neutrons but also by high-energy gamma or beta
- Pair production and annihilation
- Bremsstrahlung
- Compton scattering
- Photo-excitation
- Photo-Ionization

Relaxation of excited atoms:

- Auger X-ray and electron emission
- Photon emission

Decay of activated nuclides:

- Delayed emission of ionizing radiation
- Change of atomic number and chemical identity

Interactions without energy transfer:

- Coulomb scattering of charged particles
- Thomson / Rayleigh scattering of photons

In radiation protection dosimetry the total outcome of all the physical interactions, usually ocurring in large numbers, are either quantified by experimental measurements or Monte-Carlo calculations. The physical details of all these types of interactions are summarized in only a single dose quantity called *Absorbed Dose D* measuring the locally or mean absorbed energy as outcome.

Ionizing Radiation – Absorbed Dose D_{medium}

Absorbed Dose D is a physical dose quantity representing the mean energy ΔE_{abs} released by ionizing radiation and locally absorbed by the medium per unit mass ΔM.

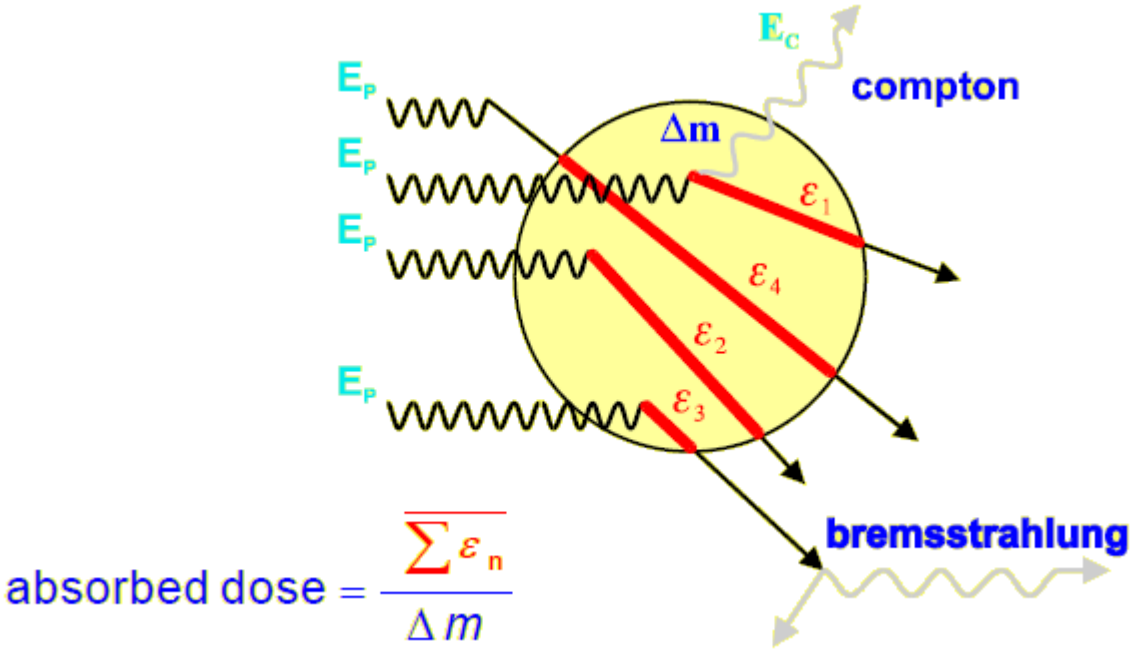
Absorbed Dose $D_{medium} := \frac{\text{mean absorbed energy } \Delta E_{abs}}{\text{unit mass } \Delta \boldsymbol{M}}$ in units of $\left[\frac{J}{kg}\right]$

In the SI system of units, the unit of measure is joules per kilogram, and its special name is gray (Gy):

$$1\ Gy = 1\frac{J}{kg}$$

The amount of energy absorbed depends on the medium which must be stated:
absorbed dose to water, air, medium X, or tissue: D_{water} , D_{air} , D_X , D_{tissue}

Ionizing Radiation – Absorbed Dose D_{medium}



From various particles crossing the mass ΔM only the absorbed portion ΔE_{abs} of kinetic energy of charged particles within the mass ΔM is counted to the absorbed dose D.

Usually not all released energy is absorbed in the same volume. In case of secondary electron equilibrium the mismatch of released and absorbed energy in ΔM is not significant.

Absorbed Dose D_{medium}- Is it appropriate?

Absorbed dose to water can be precisely defined in experimental setups and measured accurately by water calorimetry in primary standards metrology labs. And also absorbed dose to dry air can be calculated from the ionization energy and the amount of ion pairs produced.

The energy of an initial primary photon or particle is distributed in many cascaded interactions to an increasing number of ionizations and X-ray photons in the medium. When E_{kin} < 40 eV, kinetic energy from particle radiation is dissipated to thermal energy more and more effectively without ionizing.

Finally (in the human body) ionized molecules and detached electrons recombine to the original or a modified chemical form, dissipating energy to thermal heat or chemical energy.

Absorbed Dose D_{medium}- Is it appropriate?

However, ionizing radiation leads to:

- Intermediate ionizations which do not persist due to recombination
- Direct physical destruction of molecular bonds
- Chemical reactions with persisting new products, dissociation and structural changes of molecules.

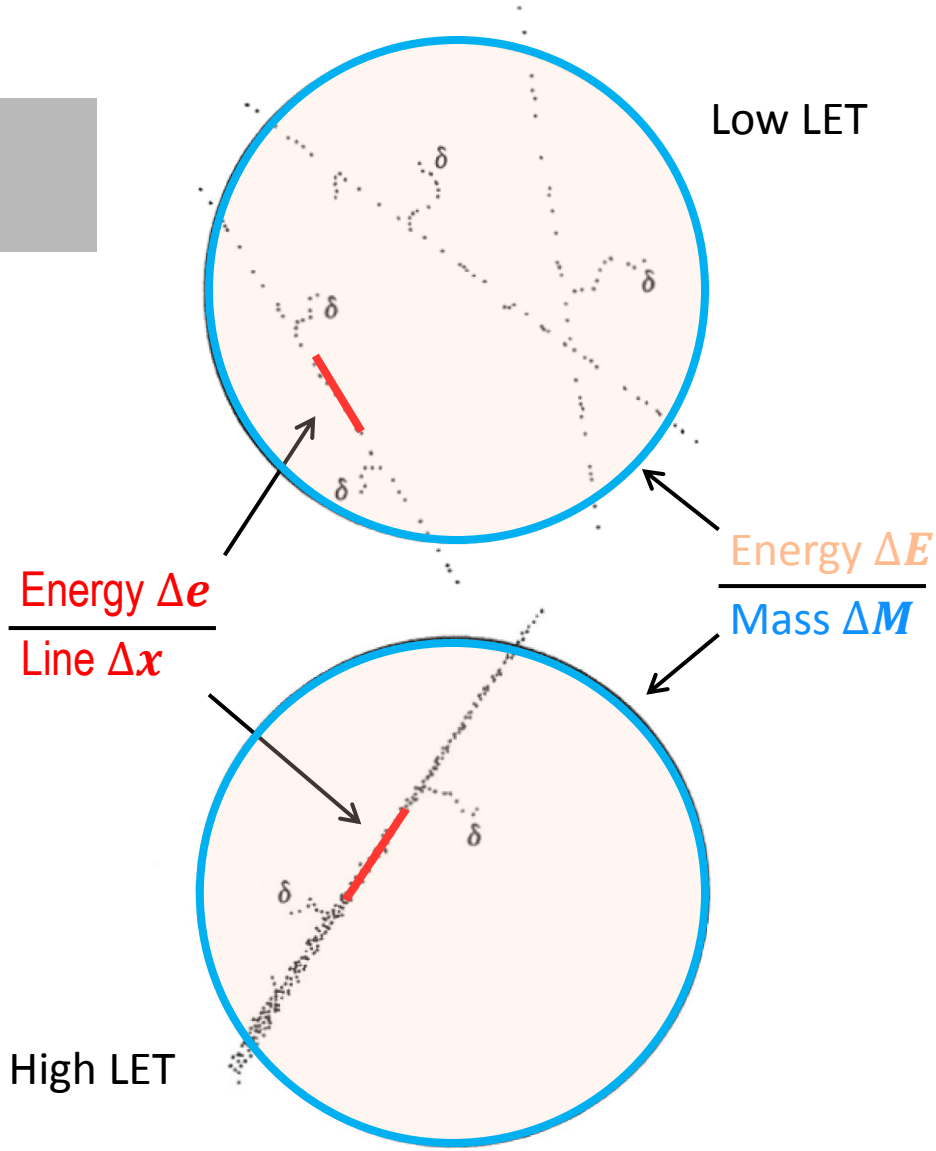
These are the origin of biological effects and health risks. Absorbed dose only measures absorbed energy per mass, and only indirectly the number of ionizations.

Historically the ion dose was used, defined as amount of ion pairs produced in medium (preferably air) to measure radiation dose.

Nevertheless, absorbed dose to tissue is the fundamental physical dose quantity used in radiation protection dosimetry, but it needs improvements to account for the effects of ionizing radiation.

Another physical quantity to describe ionizing radiation and to correlate with radiation quality is Linear Energy Transfer (LET)

Linear Energy Transfer (LET)



Both volumes with mass ΔM absorb the same amount of energy ΔE_{abs}, so the absorbed dose D is the same:

$$D_{medium} := \frac{\Delta E_{abs}}{\Delta M} \text{ in } \left[\frac{J}{kg}\right]$$

But the deposited energy Δe along a line segment Δx on the track is different.

Definition of *Linear Energy Transfer L*:

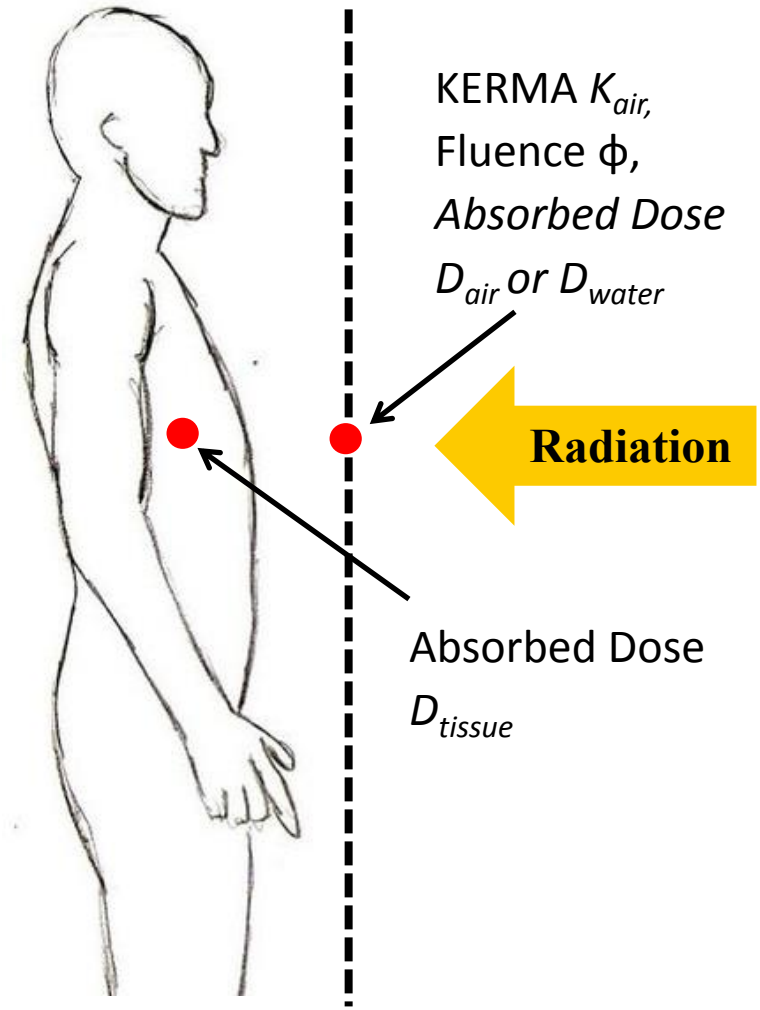
$$L := \frac{\Delta e}{\Delta x} \text{ in } \left[\frac{J}{m}\right] \text{ or } \left[\frac{keV}{\mu m}\right]$$

LET is a physical, measurable quantity which can be used to estimate the radiation quality Q(L) as function of L.

High-LET like alpha's: L > 3.5 keV/µm

Low-LET like photons: L < 3.5 keV/µm

Physical Dose Quantities for Ionizing Radiation



Absorbed dose D_{tissue} must be measured inside the human body, which is practically impossible to measure directly. LET is even much more difficult.
Suitable dose quantities, measured outside of the body, e.g. directly in the radiation field are:

- KERMA K_{air} for non-charged particles
- Fluence ϕ for all types
- $D_{air,}$ *or* D_{water} for charged particles

Using Monte-Carlo calculations or measurements with substitute phantoms, the absorbed dose in tissue can be approximated. For standard situations (calculated) conversion or correction factors are given in literature.

KERMA for Photons and Neutrons

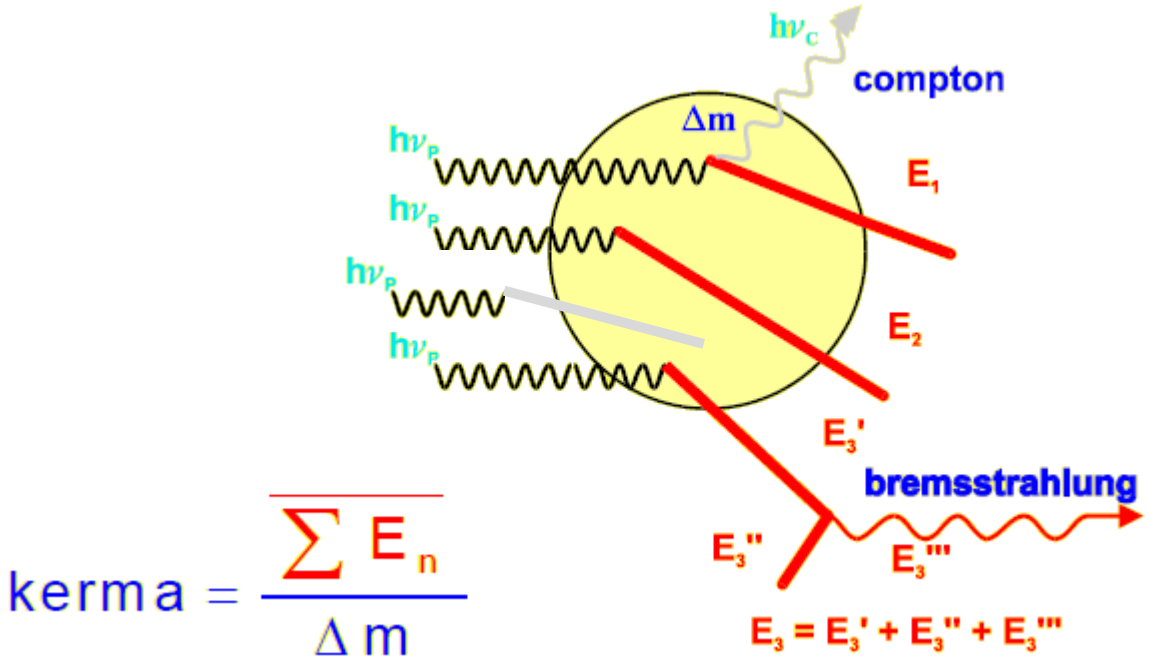
KERMA ("kinetic energy released per unit mass") is the sum of the initial kinetic energies ΔE_{tr} of the charged secondary particles which have been detached by ionization by a primary non-charged particle like a photon or neutron.

The kinetic energy ΔE_{tr} transferred in a given volume is divided by the mass ΔM of the volume, and the type of medium must be stated:

$$K_{medium} := \frac{\Delta E_{tr}}{\Delta M} \text{ in units of } Gy \left[\frac{J}{kg}\right]$$

Air Kerma is of importance in the practical calibration of instruments for photon measurement, where it is used for the traceable calibration of gamma instrument metrology facilities using a "free air" ion chamber to measure air kerma.

KERMA for Photons



$$kerma = \frac{\overline{\sum E_n}}{\Delta m}$$

Kerma dose is different from absorbed dose:

- ionization energy is not accounted for
- For low-energy photons, kerma is approximately the same as absorbed dose
- For higher-energy photons, kerma is larger than absorbed dose because some highly energetic secondary electrons and X-rays escape the volume ΔM

Flux and Fluence

Fluence

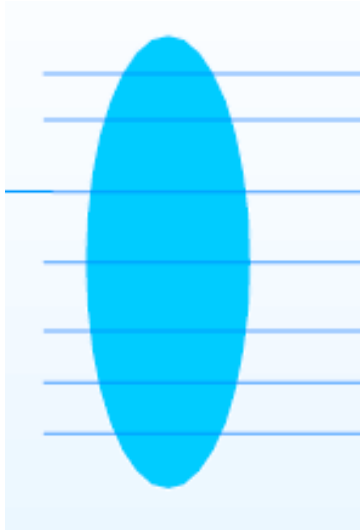
Number of particles N crossing an area A.

Unit $\left[\frac{1}{m^2}\right]$

Flux

Number of particles N crossing an area A in time t.

Unit $\left[\frac{1}{s\ m^2}\right]$



For neutron radiation, fluence is often used instead of Kerma.

Summary - Physics of Ionizing Radiation

Particles:

- Non-charged, indirectly ionising particles like photons or neutrons
- Charged, directly ionising particles like alpha's, protons, electrons, positrons, …

Interactions:

- Kinetic or electromagnetic energy of primary particles and photons is dissipated in many interactions to thermal heat and chemical modifications of the medium

Ionizations:

- During energy dissipation many ionizations are produced because required ionization energy of 1 to 40 eV is very low

Absorbed Dose:

- Physical dose quantity for measuring the amount energy absorbed by a medium

Linear Energy Transfer (LET):

- Physical quantity for the (linear) ionization density of radiation

KERMA, Fluence:

- Physical dose quantities which are easily measurable and which are used to determine absorbed dose by use of tabulated conversion factors from literature.

Radiation Damage in Biological Cells

In biological organisms, radiation damage occurs due to the ionization of atoms and molecules in cells. Ions are chemical radicals inducing chemical reactions which can break molecular bonds in proteins and other important biological molecules like DNA.

Typically, 1 to 40 eV of energy is needed to ionize a molecule or an atom.
An alpha particle with 5 MeV energy theoretically leads to 250'000 ionizations, assuming an average ionization threshold of 20 eV. In practice, secondary X-ray photons escape and kinetic energy can be dissipated otherwise without ionizations.

Human cells have very effective repair mechanisms for DNA damages, but also "self destruction" like apoptosis (controlled disintegration) or necrosis (uncontrolled breakup. Usually every cell experiences 10'000 to 1'000'000 DNA damages per day which need to be repaired (successfully). DNA damages can be detected by enzymes and repaired, but in case of erroneous repair may lead to a DNA mutation.

DNA mutations cannot be detected and repaired anymore, and persist. A single persisting DNA mutation usually does not lead to health effects, and often several, sometimes specific DNA mutations must persist in a living cell before cancer or genetic diseases may develop.

Summary – Biological Effects of Ionizing Radiation

Phase	Domain	Effects	Actors	Time Scale
1	Physics	• Collisions, Bremsstrahlung • **Ionization**	Electrons	Attoseconds
2	Chemistry	• Radiolysis, Radicals • breaking molecule bonds	Atoms Molecules	Nanoseconds
3	Biology	• **DNA repair** • **Removal of damaged cells**	DNA Enzymes	Hours
3	Biology	• Survival of mutated cells • Necrosis at high doses	Cells	Days
4	Medicine	Deterministic, acute effects, if dose above threshold and large amount of tissue is affected	Human Body	Days
		Stochastic, late effects like Cancer or genetic diseases. No lower threshold, single affected cells are sufficient		Years

Repair not successful

Health Effects of Ionizing Radiation

Deterministic effect / acute disease:

- Tissue or whole organs are affected due to significant amount of cells experiencing necrosis or malfunction
- Acute diseases develop within a short time of few days
- Effect and organ specific dose threshold often exists below which the effect does not occur
- Grade of effect increases with radiation dose

Deterministic effects are well known from external beam radiation therapy of cancer when a patient is by intention exposed to high doses of ionizing radiation and the radiation induced acute diseases are accepted as unavoidable side effect of the treatment when the primary goal is the cure from cancer.

Deterministic Effects

In order to assess deterministic effects the dose quantity *Organ Absorbed Dose* is used, which represents the total absorbed energy E_T from ionizing radiation to the whole organ (or tissue) T with mass M_T:

Organ Absorbed Dose in organ T $D_T := \frac{\text{absorbed energy } E_T}{\text{mass } M_T}$ in units of $[\mathrm{G}y]$

Like the (microscopic) physical dose quantity *Absorbed Dose* D_{tissue} the (macroscopic) *Organ Absorbed Dose* D_T is not measurable but can be calculated. Lower threshold and upper limit dose values which should not be exceeded to avoid a specific deterministic effect are known from clinical experience. Therefore, the *Organ Absorbed Dose* D_T is a *Protection Dose Quantity*.

Examples of deterministic effects are:

- Erythema / reddening of the skin: 2 Gy to small areas of few cm diameter
- Acute radiation syndrome: 1 Gy to whole body
- Hair loss
- Reduction of white blood cells
- Cataracts in the eye lens

… and many more …

Health Effects of Ionizing Radiation

Stochastic effects / delayed disease:

- Only persisting DNA mutations are relevant as stochastic effect
- Genetic diseases: DNA mutations in gonads (ovaries, testes) leading to genetic diseases in the offspring of the individual exposed to the radiation
- Cancer: several DNA mutations survive and accumulate in single cells, which then may start proliferating uncontrolled at some time
- Probability of stochastic effects increases with radiation dose
- Grade of effect itself (e.g. “size of cancer”) usually independent of radiation dose
- No lower dose threshold for inducing stochastic effects
- Large uncertainty in predicting stochastic effects induced by low doses (LNT model)

What is the appropriate protection dose quantity for stochastic effects?
(Like *Organ Absorbed Dose* for deterministic effects)

Challenges in Radiation Protection Dosimetry

1. Define a usable dosimetry system which allows to quantify (non-physical) health risks and relate them to exposure to (physical) ionizing radiation.
2. Establish safe dose limits for the exposure of people on the basis of a justifiable risk, especially because stochastic effects have no lower threshold.
3. Provide measureable dose quantities to optimize radiation protection

Two cooperating organizations promote and document the developments in the field of radiation protection and dosimetry:

- ICRP (**I**nternational **C**ommission on **R**adiological **P**rotection)
- ICRU (**I**nternational **C**ommission on **R**adiation **U**nits and Measurements)

Their publications often serve as basis for mandatory national regulations in radiation protection of workers and the general public. There is a long history, starting in 1928, and development has not finished yet.

Other organisations like IAEA, Euratom, ISO, etc., often provide documents with additional standards and recommendations, or advices for use and application.

Dose Quantities for Radiation Protection

The system of dose quantities in radiation protection uses three categories:

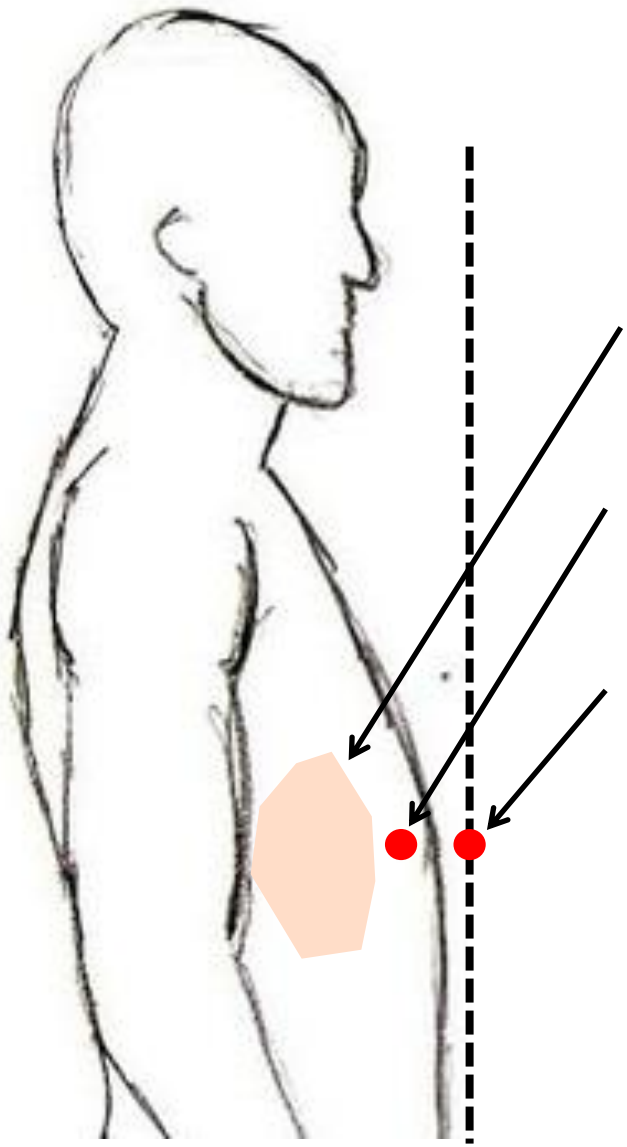
- Protection dose quantities for dose limits
- Operational dose quantities for monitoring of exposure
- Physical dose quantities for primary measurement of radiation

Protection dose quantities take into account biological effects induced in man. They are not technically measurable, but deduced from epidemiological studies. Inherently, protection dose quantities represent populations and cohorts, and in principle cannot be accurate for a specific individual like 'John Smith'.

Operational dose quantities are defined as measureable which should provide conservative (upper) dose estimates for the protection dose quantities. Operational dose quantities cannot behave exactly like protection dose quantities, because point of measurement is not inside organs, but inside the body, and phantom medium is different from various types of biological tissue.

Physical dose quantities like KERMA, fluence, absorbed dose to water, etc. are measureable and form the basis for the calculation of protection and operational dose quantities.

Dose Quantities for Radiation Protection



Protection Dose Quantity

Organ Absorbed Dose D_{organ}

Operational Dose Quantity

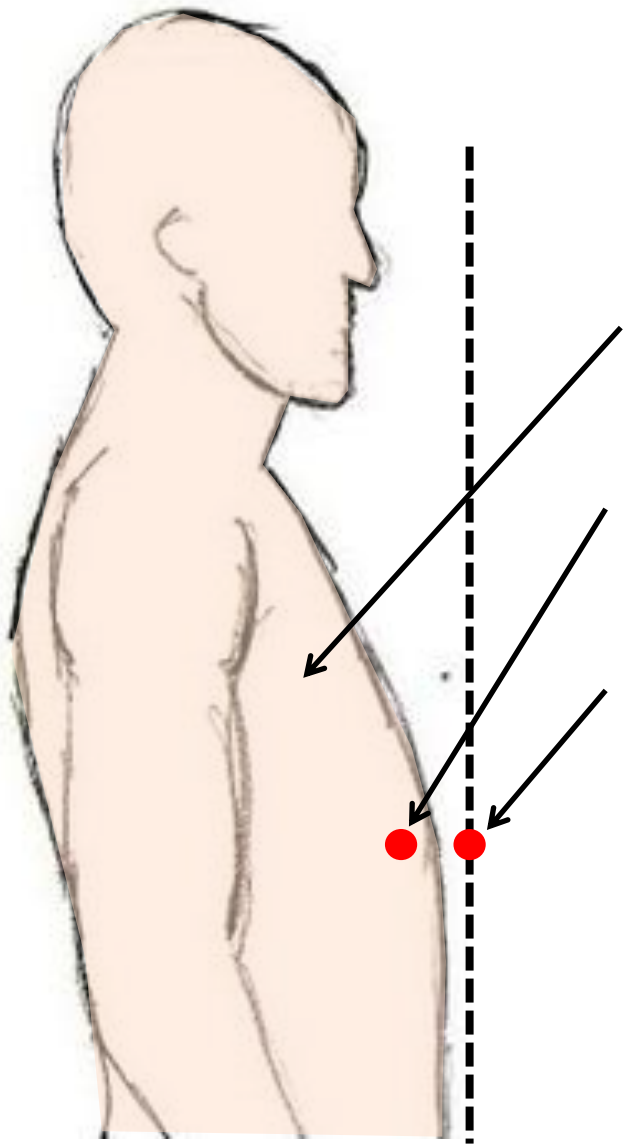
Physical Dose Quantity

KERMA $K_{air,}$ Fluence ϕ

Place of personal dosemeter

Radiation

Dose Quantities for Radiation Protection



Protection Dose Quantity
for the whole body

Operational Dose Quantity

Physical Dose Quantity
KERMA $K_{air,}$ Fluence ϕ
Place of personal dosemeter

Radiation

Epidemiological Studies for Protection Dose Quantities

Epidemiological and clinical studies of ionizing radiation exposure:

- Atomic bomb survivors of Hiroshima and Nagasaki
- Patients, physicians and scientists from the early days of X-ray applications
- Workers in nuclear industry and other branches where ion. radiation is/was used
- Patients treated with radiation therapy
- …

In such studies, the actual exposure of each individual often occurred under conditions which were not well known and not well controlled. The health effects of ionizing radiation had to be reconstructed retrospectively as good as possible. Which health effects are due to ionizing radiation and not due to other detriments? Which kind of radiation? Exposure situation? Geometry? Amount of radiation exposure? Individual properties and co-factors? …

A lot of research has been done and is still ongoing …

Epidemiological Studies for Protection Dose Quantities

Principal results: For the same amount of radiation exposure, the health effects of ionizing radiation are dependent on the type of radiation, the direction of radiation on the body, the specific organs affected, on age, gender, partial or whole body exposure, etc …

Influencing Factor		Approach
Type of radiation and quality	→	Radiation weighting factors w_R
Type of organ affected	→	Organ weighting factors w_T
Gender male or female	→	Gender anatomical model
Age	→	Age-dependent anatomical models and protection dose limit values
Direction of radiation	→	Geometries

These influencing factors are taken into account in definitions of protection dose quantities, limit values, and calculation of conversion coefficients.

Equivalent Dose H_T to include Radiation Quality

Starting point is the protection dose quantity *Organ Absorbed Dose* D_T *in organ T* (unit Gy) which is already used for deterministic effects, now extended to account for radiation quality.

Equivalent Dose H_T is a protection dose quantity taking into account the quality and type *R* of radiation by weighting factors w_R:

Equivalent Dose $H_T := \sum_R D_{T,R} \cdot w_R$ in units of Sievert [Sv]

The weighting factors have been derived from epidemiological studies. The same amount of absorbed organ dose D_T leads to different risks of stochastic effects depending on the type (photon, neutron, alpha) and quality (energy) of radiation. For each radiation type *R* the organ absorbed dose $D_{T,R}$ is counted and weighted separately.

Radiation Weighting Factors w_R, ICRP 60 (1990)

Type of radiation	Quality E_{kin}	w_R
X-ray, gamma, beta-particles	all	1
Neutrons	< 10 keV	5
	10 keV … 100 keV	10
	100 keV … 2 MeV	20
	2 MeV … 20 MeV	10
	20 MeV …	5
Protons (not secondary protons)	2 MeV …	5
Alpha particles, fission products, heavy ions	all	20

Not used anymore today, but important for comparing old an new protection dose values.

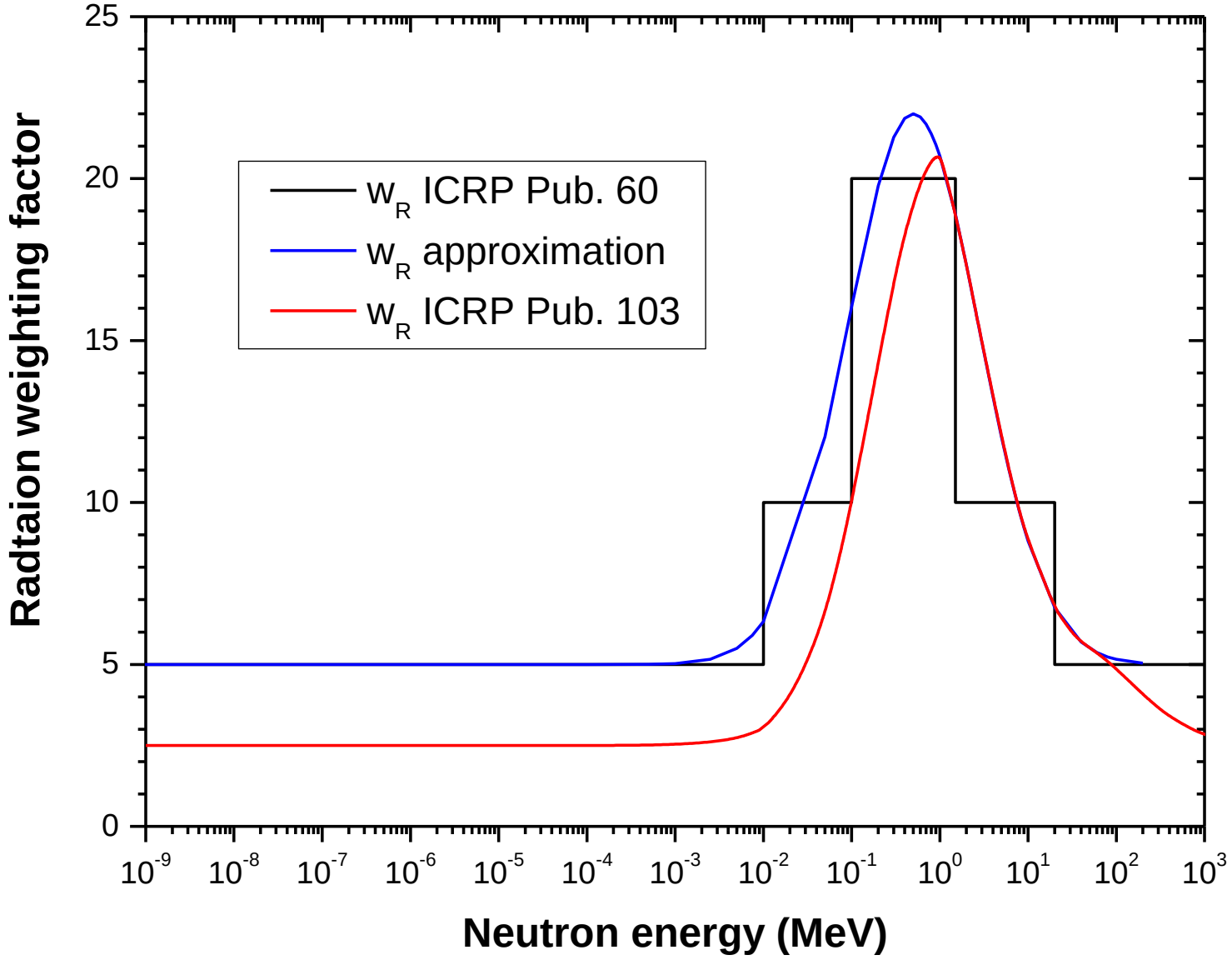
Radiation Weighting Factors w_R, ICRP 103

In ICRP publication 103 (2007) the radiation weighting factors have been revised:

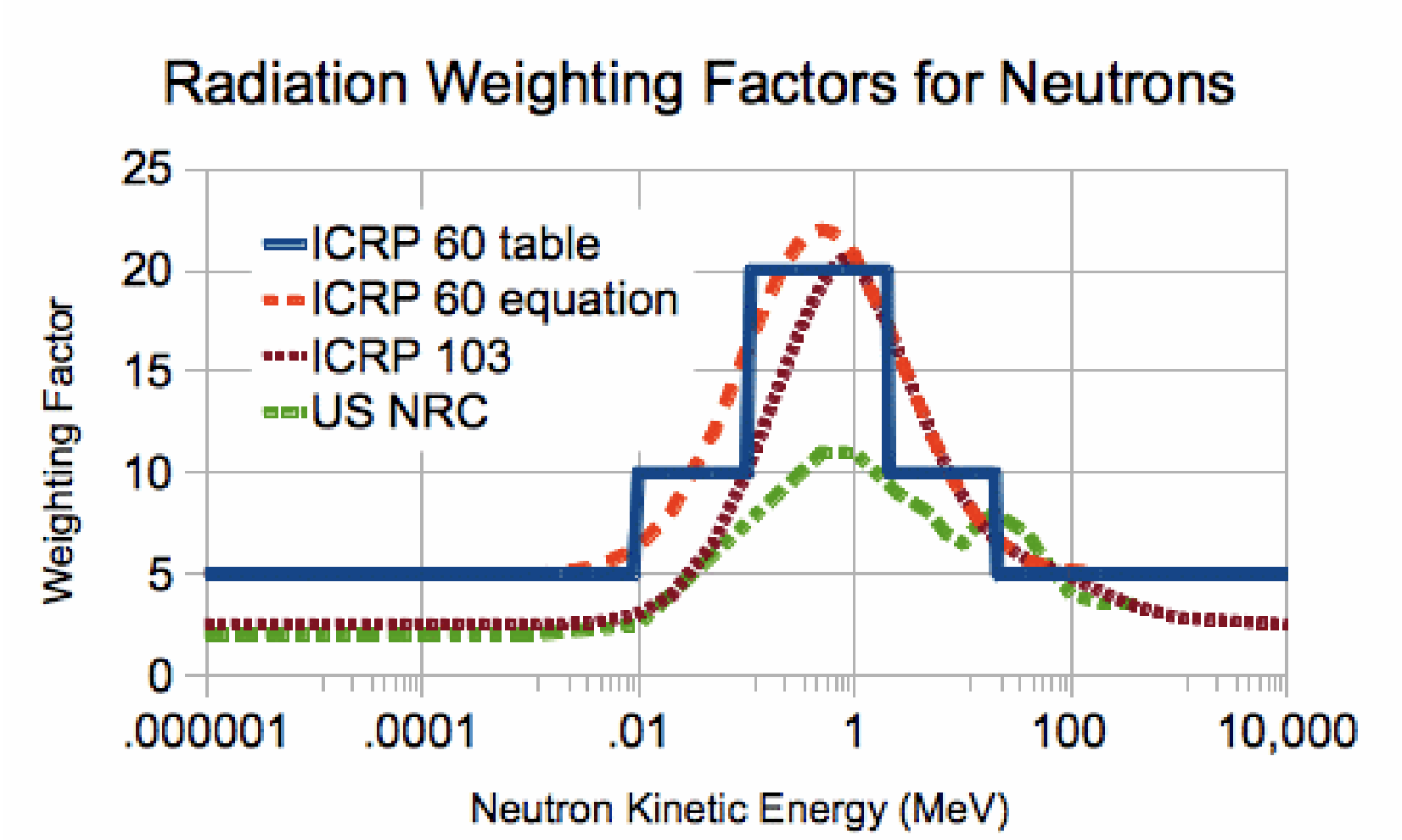
Radiation	Quality E_{kin}	w_R
X-ray, gamma, electrons, positrons, muons	all	1
Neutrons	< 1 MeV	$2.5 + 18.2 \times e^{-(\ln(E))^2}/6$
	$1 - 50$ MeV	$5.0 + 17.0 \times e^{-(\ln(2\times E))^2}/6$
	50 MeV …	$2.5 + 3.25 \times e^{-(\ln(0.04\times E))^2}/6$
Protons, charged pions	2 MeV …	2
Alpha, nuclear fission products, heavy ions	all	20

But national regulations like the US Nuclear Regulation Commission (NRC) may use other radiation weighting schemes.

Radiation Weighting Factors w_R for Neutrons



Radiation Weighting Factors w_R for Neutrons



Attribution: Ytrottier at English Wikipedia

Effective Dose E including Organ Sensitivity

Effective Dose E is a protection dose quantity taking into account the different sensitivity of human organs and tissues *T* to ionizing radiation by weighting factors w_T:

Effective Dose $E := \sum_T H_T \cdot w_T$ in units of Sievert [Sv]

The weighting factors have been derived from epidemiological studies. The same amount of equivalent dose H_T leads to different risks of stochastic effects depending on the organ. *Effective Dose* is defined for the whole body and has the unit Sievert Sv.

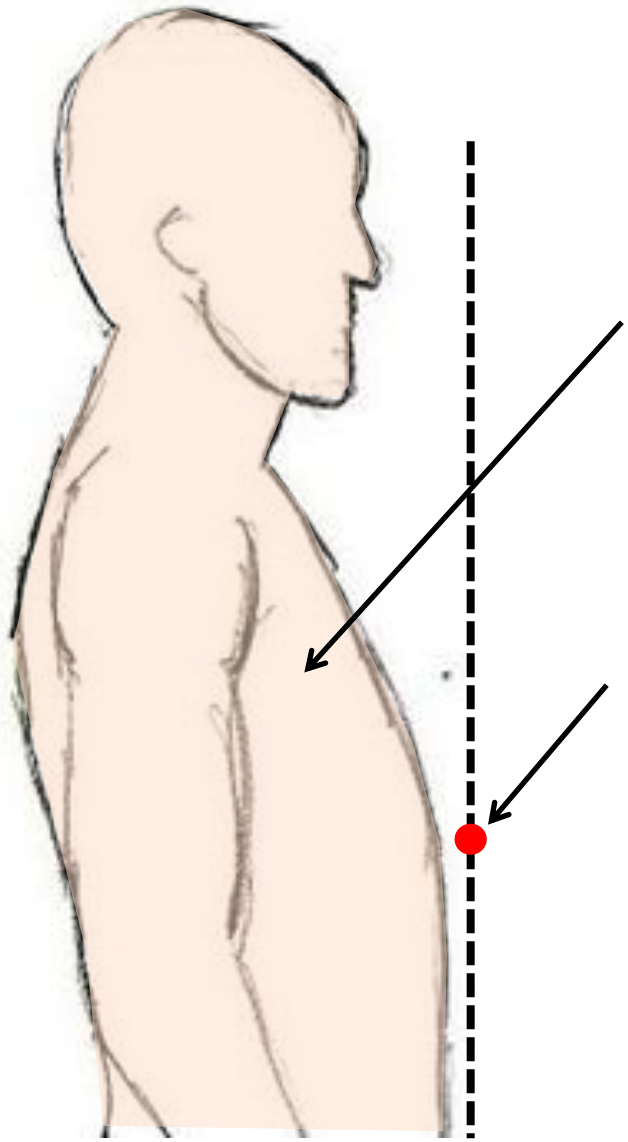
The organ weighting factors w_T are averages over male and female genders, all ages, and all body weights of the adult population. Therefore *Effective Dose* is not a measurable dose quantity which accurately measures the stochastic risk for a specific individual, but is a conservative, upper estimate.

For complete uniform irradiation $\sum_T w_T = 1$, and *Effective Dose E = Whole Body Equivalent Dose* H_{Body}. For partial irradiation only sum up H_T of affected organs.

Organ Weighting Factors w_T

Tissue/ Organ	ICRP 60 (1990)	ICRP 103 (2007)
Gonads	0.2	0.08
Red Bone Marrow	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Oesophagus	0.05	0.04
Thyroid	0.05	0.04
Bone Surface, Skin, …	0.01	0.01
Brain, Salivary Glands	-	0.01
Remainder of body	0.05	0.12
Sum of weights w_T	1	1

Dose Quantities for Radiation Protection



Protection Dose Quantity
for the whole body: *Effective Dose E*

Physical Dose Quantity
KERMA $K_{air,}$ Fluence ϕ
Place of personal dosemeter

Radiation

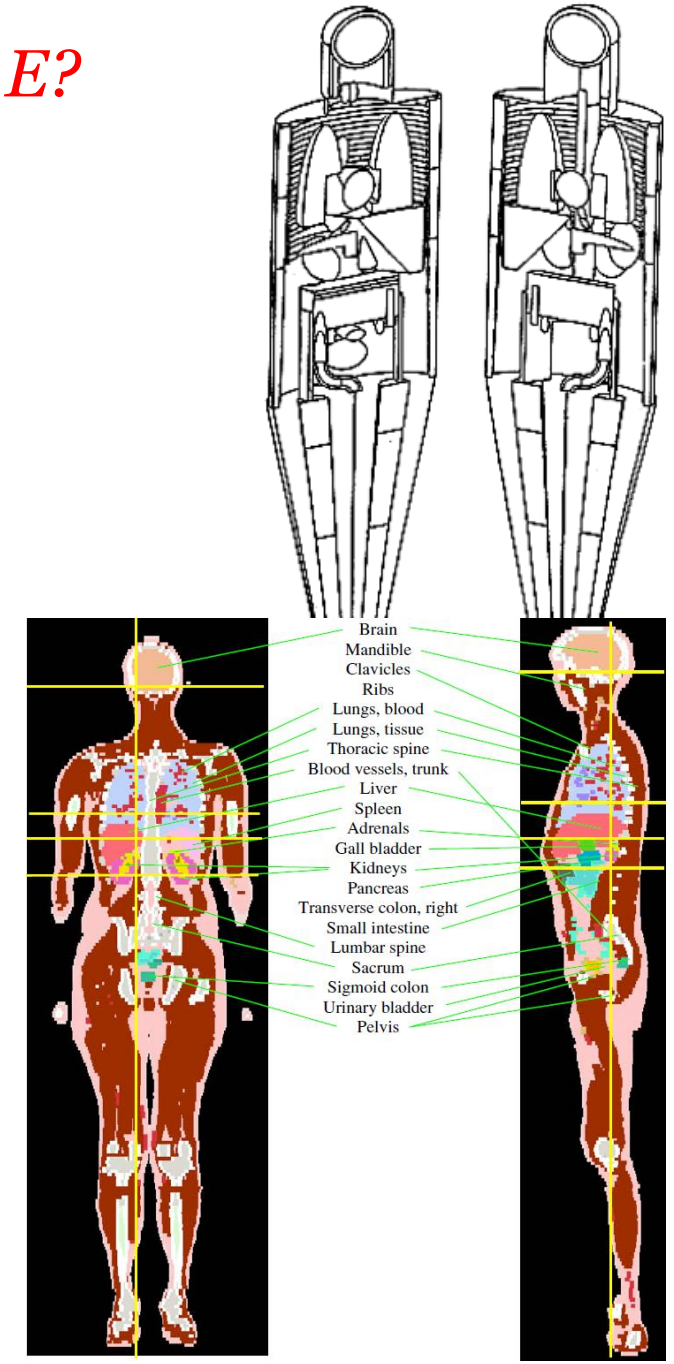
Calculation *Effective Dose E?*

Effective Dose E and *Organ Equivalent Dose* H_T are based on the protection dose quantity *Organ Absorbed Dose* D_T which cannot be measured inside the body.

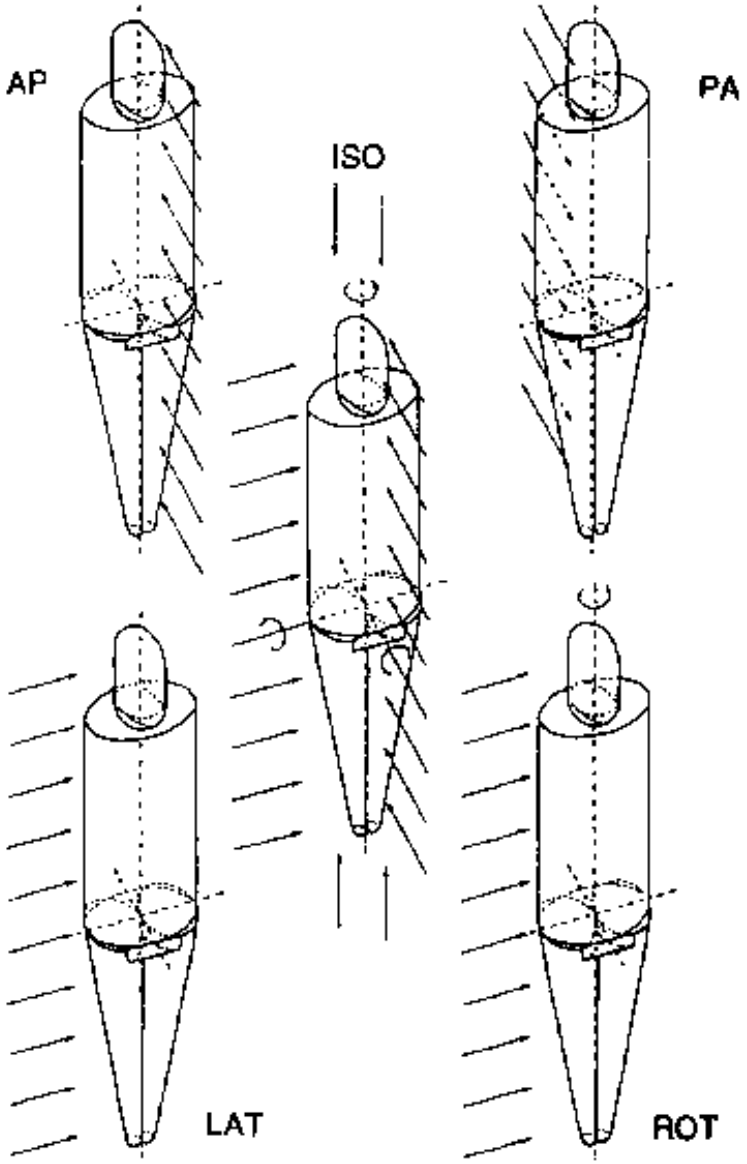
Computation of conversion coeffcients relating effective dose to physical quantities for standard conditions with defined irradiation geometries, monoenergetic radiations, and anthropomorphic phantoms including most organs and tissues in the body with their shape and atomic composition.

Anthropomorphic phantoms:

- „Reference Man“ and „Reference Woman“ (ICRP 1975, updated in 2002)
- Geometric phantoms (MIRD-models, 1968)
- Voxel Models (ICRP 110, 2009)



Geometries for Calculation of Effective Dose

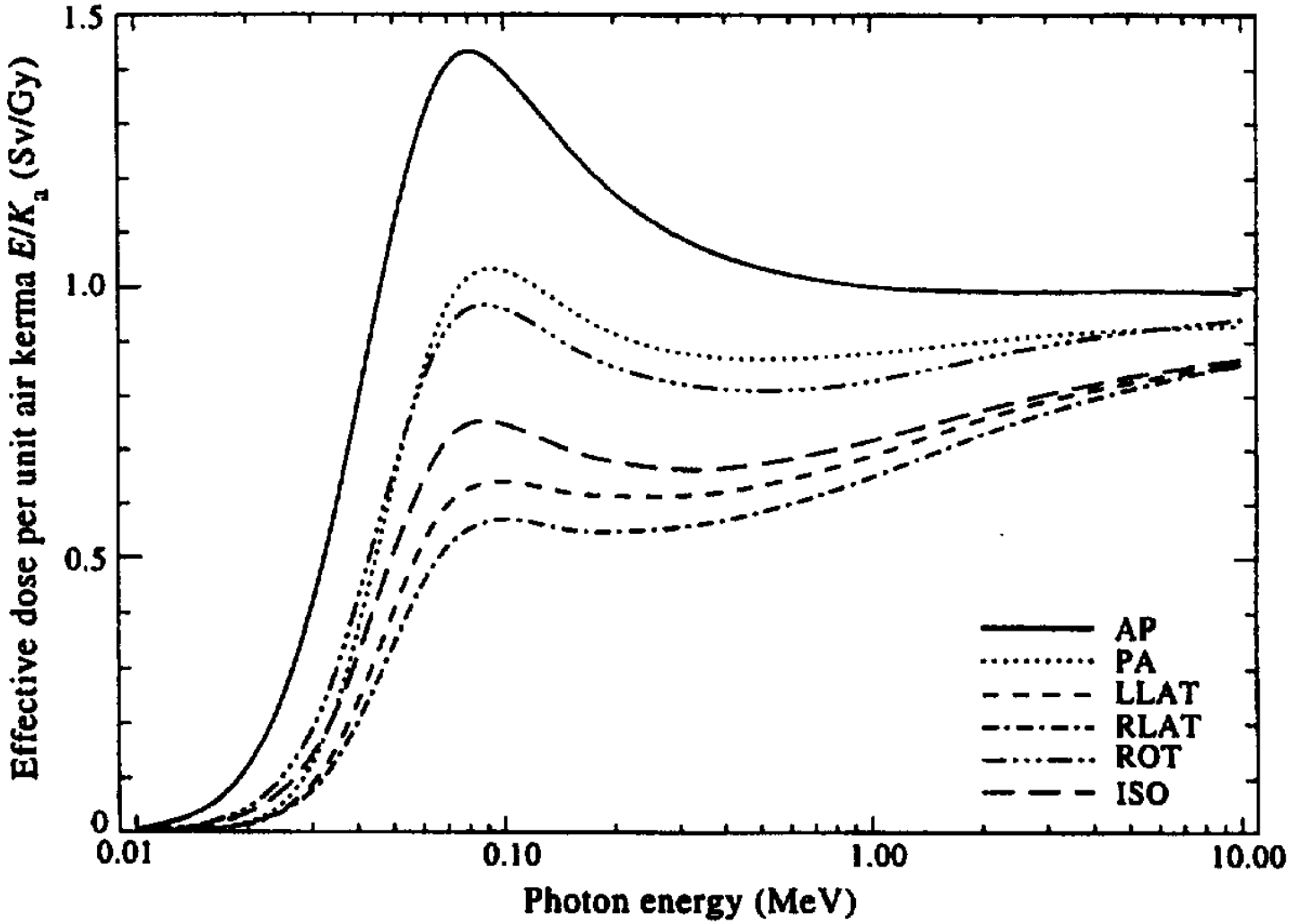


Effective dose will depend on the direction of the radiation field:

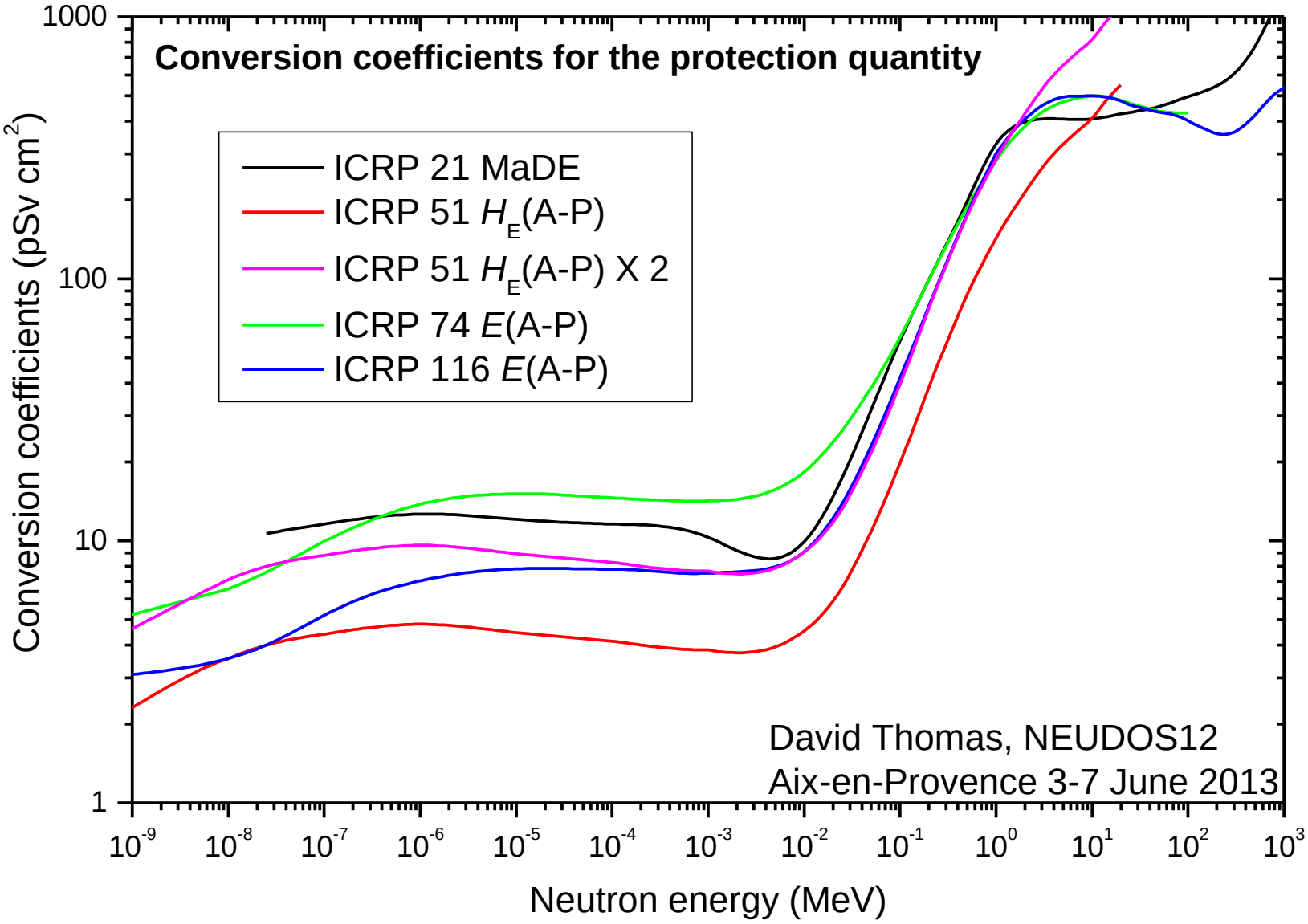
- AP (antero-posterior) irradiation from in front
- PA (postero-anterior) irradiation from behind
- LLAT (left-lateral) and RLAT (right-lateral) for irradiation from left or right
- LAT for the average of LLAT and RLAT
- ROT for rotational irradiation in the horizontal plane
- ISO for spherical irradiation (ROT and from above and below)

Conversion Coefficients for External Radiation

Example: Conversion coefficient $^{E}/_{K_{Air}}$ (Sv/Gy) for
Effective Dose E per air kerma K_{Air} for photons, ICRP 74



Conversion Coefficients for Neutrons *E/Fluence*



Summary Protection Dose Quantities

- *Effective Dose E*: most used protection dose quantity for estimating stochastic health risk to the whole body. Unit of *E* is sievert (Sv). It includes all known factors which influence the health risk, like radiation type, organ sensitivity, gender, age, direction and geometry of the radiation field. *E* is used to define dose limits in radiation protection.
- *(Organ) Equivalent Dose* H_T: used for estimating deterministic effects in single organs and without the organ sensitivity. Unit of H_T is sievert (Sv), and H_T is also used to define dose limits.
- *Organ Absorbed Dose* D_T: physical dose quantity with units of gray (Gy).

Not discussed:

- *Committed Effective Dose* E_{50} and *Organ Equivalent Dose* $H_{T,50}$ for the incorporation of radionuclides and summed up over a retention time of 50 years in units of sievert [Sv].
- *Collective Effective Dose S* for the estimation of health risks for a population in units of man-sievert [man-Sv]. It is the summation of effective doses of groups of people.

Be aware that the names of dose quantities are dedicated names and might lead to confusion: *Equivalent Dose* has different definition than *Dose Equivalent* (see later).

How to "measure" *Effective Dose* in Practice?

Conversion coefficients like $^{E}/_{K_{Air}}$ are not practical for radiation protection dosimetry:

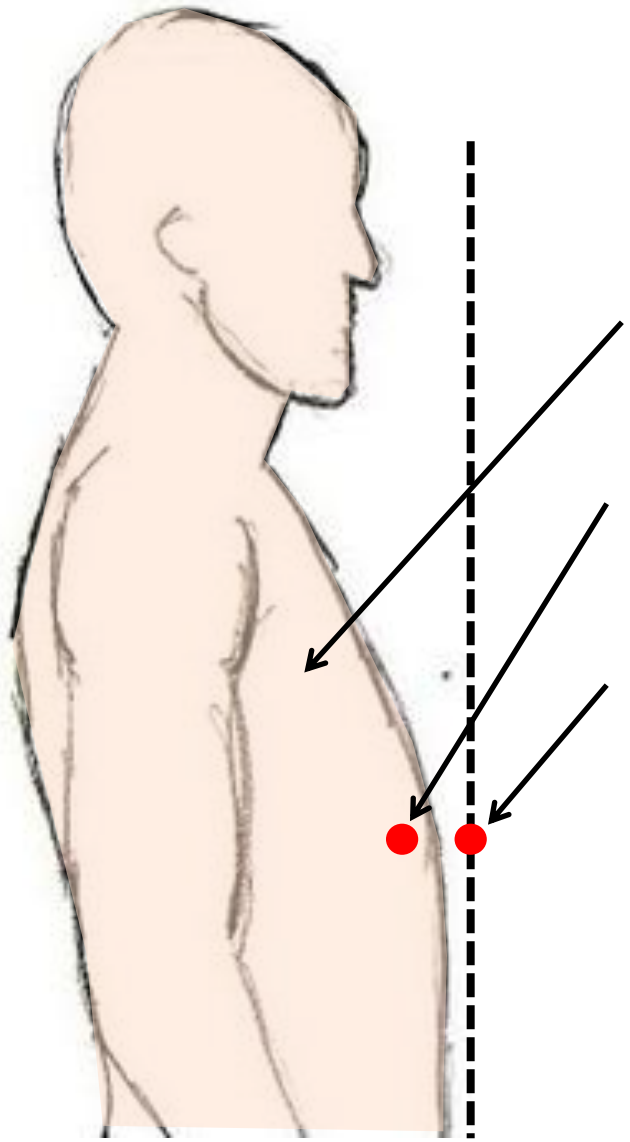
- The type, energy and direction of the ionizing radiation is usually not known
- Physical dose quantities measured outside of the human body do not correlate well with effective dose. The radiation field is modified and backscattered by the body
- Conversion coefficients are sophisticated to calculate

The remedy is to define a new category of *Operational Dose Quantities:*

- Based on absorbed dose to "ICRU tissue", which is considered to be equivalent to human tissue regarding absorption, attenuation and scattering of ionizing radiation. Density of 1 g/cm^3 , mass composition: 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen. No stable material can be made. "ICRU tissue" is used only for calculations
- Behaves as good as possible like a protection dose quantity, e.g. *Effective Dose,* for all radiation types and energies, etc.
- Measurable

The main use of the operational dose quantities is to serve as a design goal for personal dosemeters, instruments, etc. which are easier to realize in practice.

Dose Quantities for Radiation Protection



Protection Dose Quantity
for the whole body: *Effective Dose E*

Operational Dose Quantity

Physical Dose Quantity
KERMA $K_{air,}$ Fluence ϕ
Place of personal dosemeter

Radiation

Operational Dose Quantity *Dose Equivalent H*

The *Dose Equivalent H* at a point in tissue is obtained from absorbed dose at the point by multiplying it by the quality factor:

$$H = Q(L) \cdot D \text{ in units of sievert (Sv)}$$

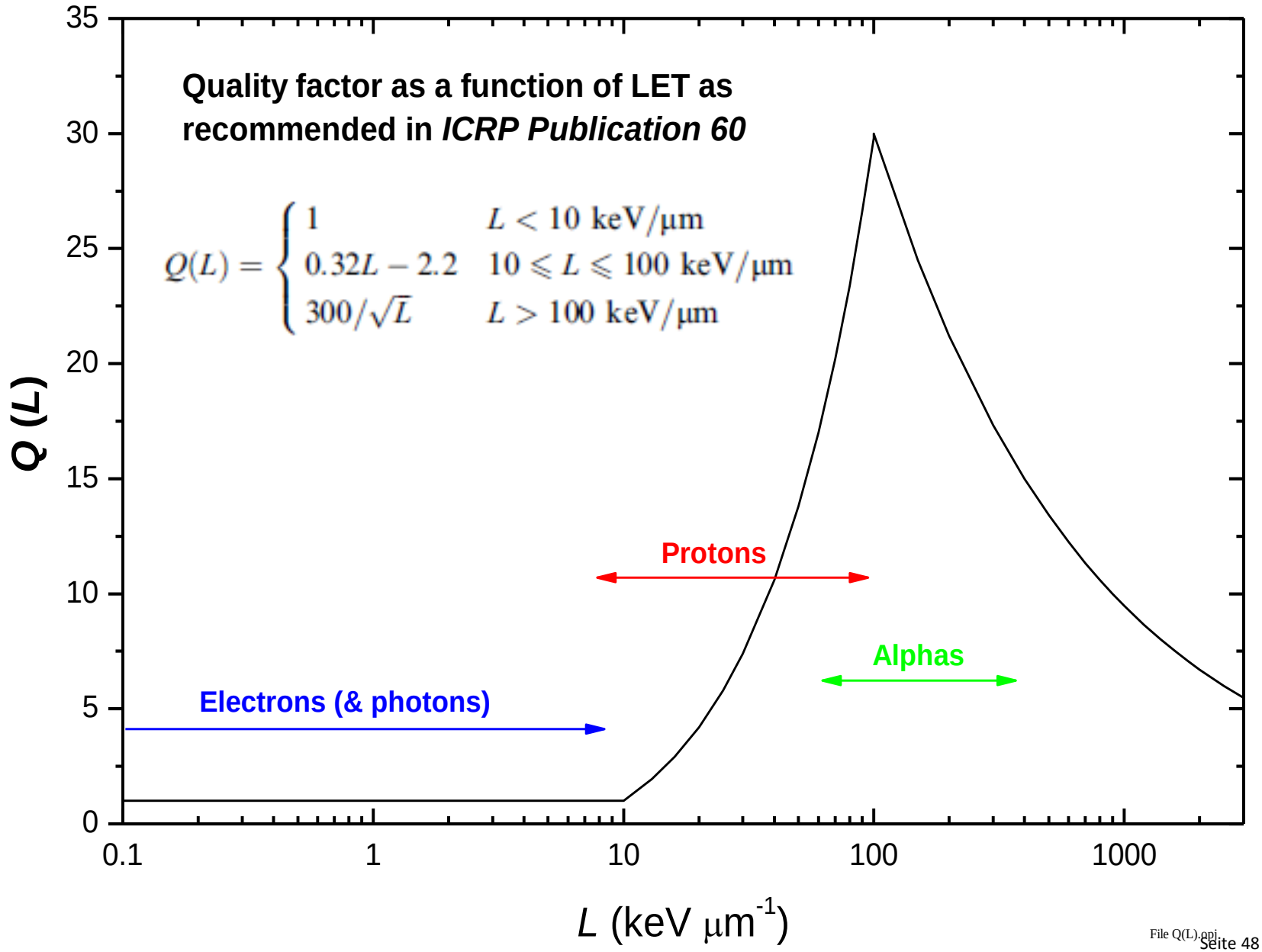
- *D* is the absorbed dose in "ICRU tissue" at a point inside a phantom
- *Q(L)* a quality factor weighting the relative biological effectiveness of radiation as a function of the linear energy transfer *L* of a charged particle in water.

Q(L) has been defined by organizations ICRP and ICRU, after compiling data from radiobiological and epidemiological studies.

Q(L) is based on absorbed dose to "ICRU tissue" *D* as a (very) small point measurement.

Linear energy transfer *L* or ionization density is measurable and known in water.

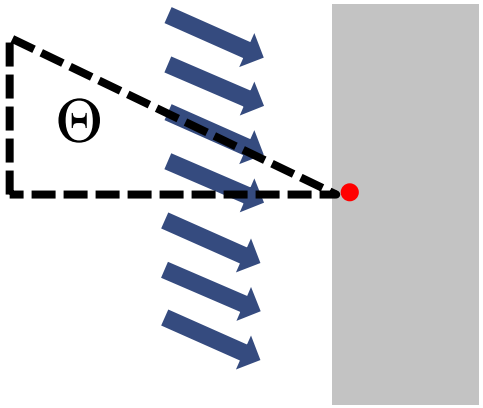
Quality Factor based on Linear Energy Transfer



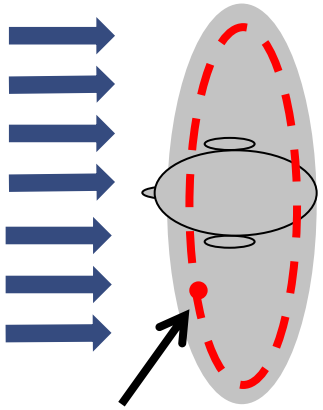
Personal Dose Equivalent $H_p(d,\theta)$

The *Personal Dose Equivalent* $H_p(d,\theta)$ is defined using a sphere with 30 cm Ø made of "ICRU" material, but which does not exist. In principle the "ICRU-sphere" approximates the human body and is used only in calculations. In practice water phantoms, in the form of a slab made of PMMA and filled with water, are used to establish reference conditions for calibration and dose measurements.

$H_p(d,\theta)$ depends on depth d in mm inside the body and angle of incidence θ. As standard situation, the radiation comes from in front, and the point of interest is in the chest of a person. Angle θ = 0 is usually not indicated.



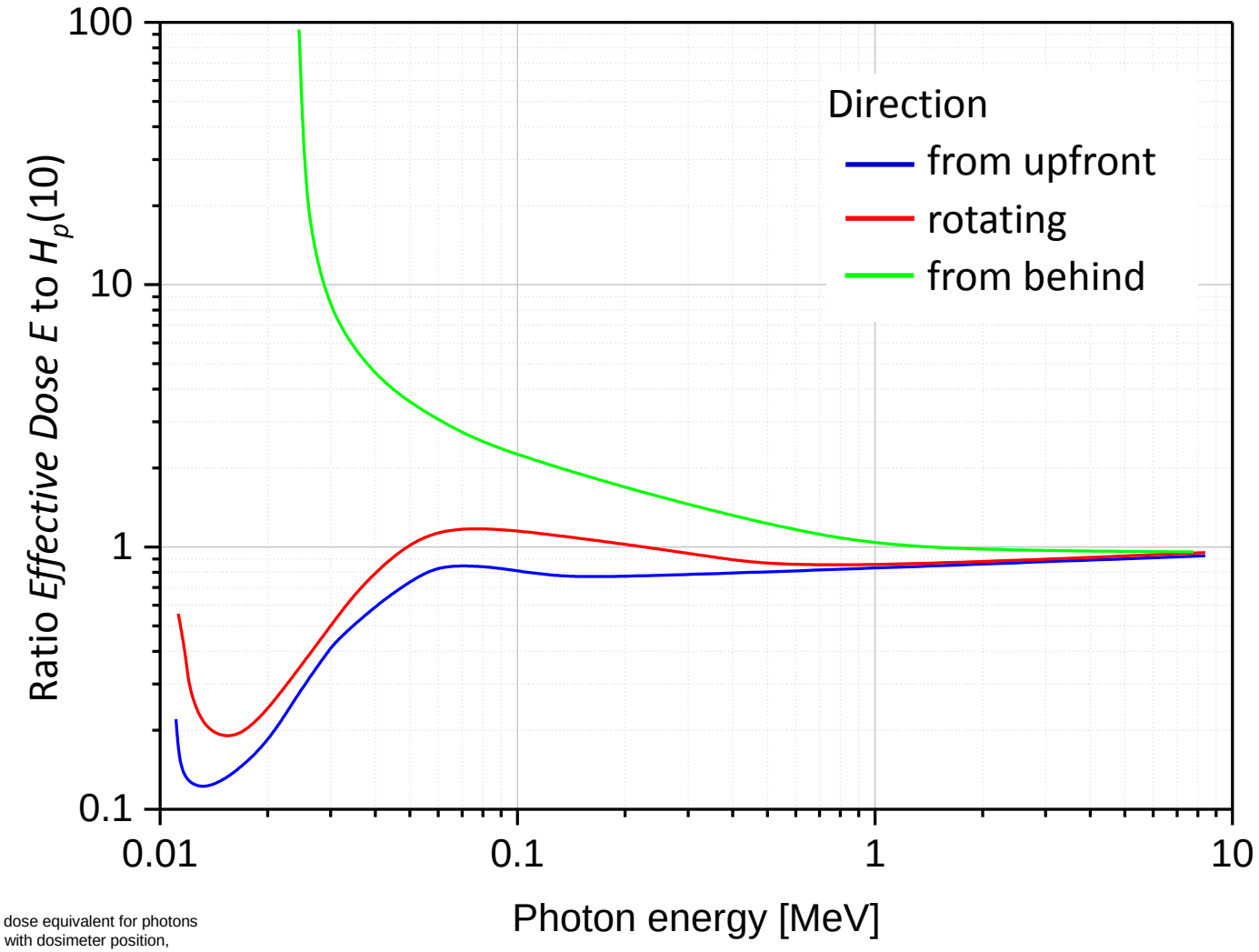
Water phantom



Depth d in [mm]

In principle the point of interest should be facing towards the radiation field for proper dose estimation, so θ = 0, and $H_p(10)$ should be independent of θ.

Ratio of Effective Dose E to Operational Dose $H_p(10)$



Zankl, Personal dose equivalent for photons
and its variation with dosimeter position,
Health Physics, Vol 76, Issue 2, page 162-170 (1999)

Ambient and Directional Dose Equivalent

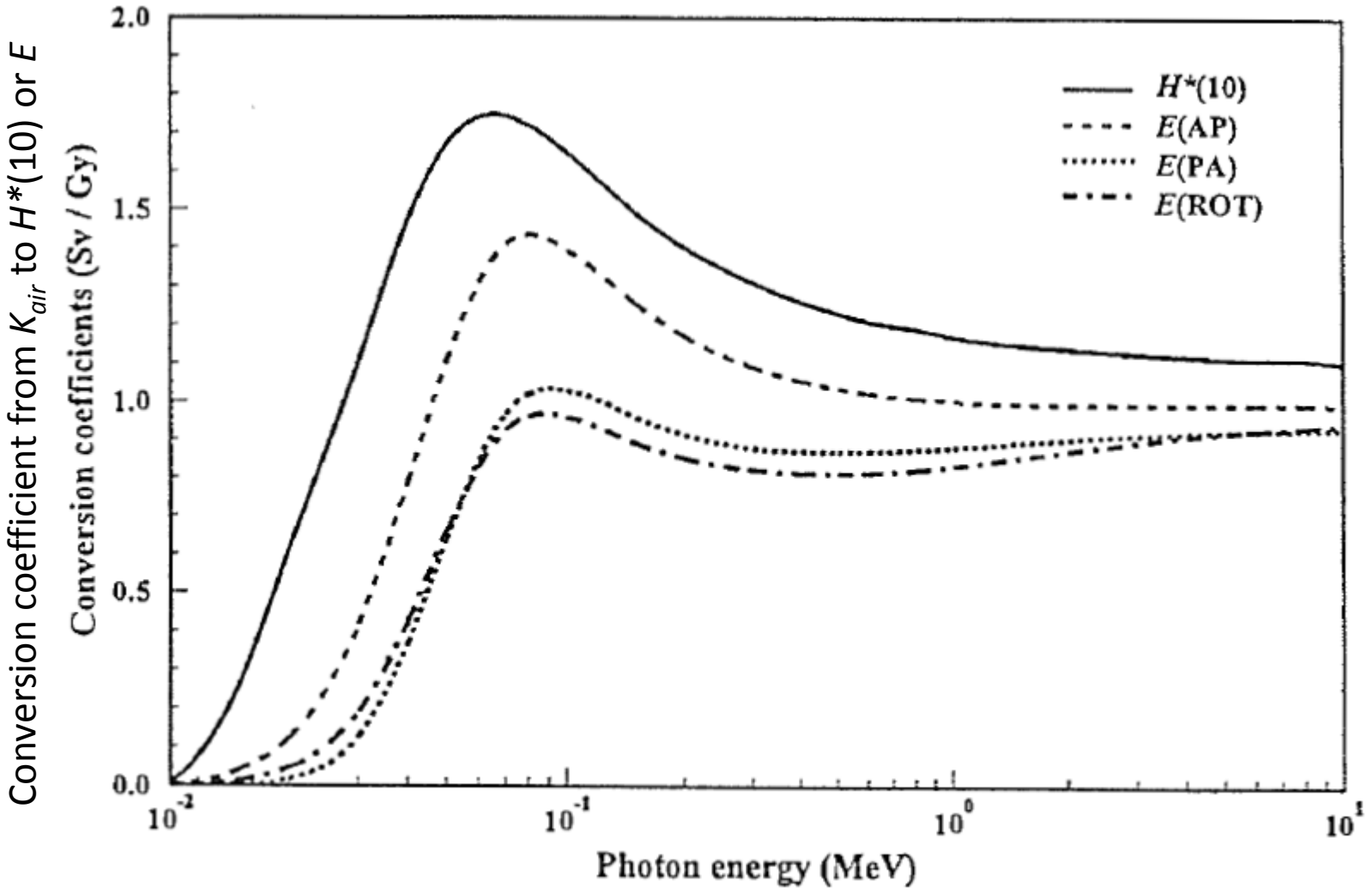
The presense of a phantoms or the human body influences the dose value significantly due to backscattering, attenuation and absorption.

The *Ambient Dose Equivalent H**(d) and the *Directional Dose Equivalent H'*(d, θ) are defined as corresponding quantities to the personal dose equivalents, but where no phantom is present, but giving the same numerical dose values like H_p(d) or H_p(d,θ) determined on a phantom.

The goal is that ambient and directional dosemeters measuring "free in air" should give the same dose values as personal dosemeters worn by a person in the same place.

Relationship of Operational to Protection Dose Quantities

Operational dose quantities are defined such that they are (always) a conservative, upper estimate for the protection dose quantity.

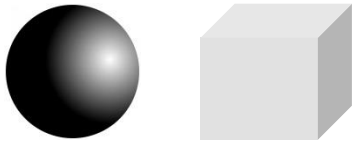


Relationship Operational and Protection Dose Quantities

The operational dose quantities should be used as conservative estimates for doses below protection dose limits. For doses near to or exceeding the limits or investigation levels, additional information on the radiation characteristics of the workplace and on the response characteristics of the dosemeter should be used to confirm that it is appropriate to use the operational quantities to estimate the correponding protection dose quantity.

Operational Quantity	Protection Quantity
Personal Dose Equivalent (PDE) $H_p(10)$	*Effective Dose E* for whole body
*Ambient Dose Equivalent H**(10)	*Effective Dose E* for whole body
Personal Dose Equivalent $H_p(0.07)$	*Organ Equivalent Dose* H_{Skin} per area*
Directional Dose Equivalent H'$(0.07,\theta)$	*Organ Equivalent Dose* H_{skin} per area*
PDE $H_p(3)$ or $H_p(0.07)$ at the head	*Organ Equivalent Dose* $H_{eye\ lens}$
$H_p(0.07)$ for X-ray, electrons, alphas $H_p(10)$ for neutrons at the fingers or toes	*Organ Equivalent Dose* $H_{extremities}$ for the extremities
	* Limit value depends on size of area and must be known

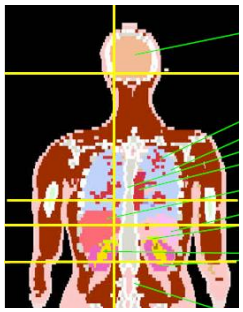
System of Dose Quantities (ICRP 74)



Calculated using $Q(L)$ and sample phantoms (sphere or slab) validated by measurements and calculations

Physical quantities

- Fluence, Φ
- Kerma, K
- Absorbed dose, D



Calculated using w_R, w_T, and anthropomorphic phantoms

Operational quantities

- Ambient dose equivalent, $H^*(d)$
- Directional dose equivalent, $H'(d,\Omega)$
- Personal dose equivalent, $H_p(d)$

Protection quantities

- Organ absorbed dose, D_T
- Organ equivalent dose, H_T
- Effective dose, E

Compared by measurement and calculations (using w_R, w_T, and anthropomorphic phantoms)

Related by calibration and calculation

Monitored quantities: Instrument responses

Summary - System of Dose Quantities (ICRP 74)

Protection quantities

- are defined to estimate the risk for stochastic effects and deterministic health risks
- are used for dose limits

Operational quantities

- are defined for measurements and assessment of doses
- are defined in the person and (for calibration) in simplified phantoms
- should provide reasonably precise (in general conservative) estimates of protection quantities

Physical quantities for radiation measurements

Calculated conversion coefficients provide the link between physical and radiation protection quantities

Personal dosemeters and instruments are supposed to provide reasonable accurate and precise estimates of operational quantities.

Dose Limits Recommendations in ICRP 103

Type of Dose Limit	Limit on Dose from Occupational Exposure	Limit on Dose from Public Exposure
Effective Dose	20 mSv per year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv	1 mSv in a year
Equivalent Dose to the Lens of the Eye	20 mSv per year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv	15 mSv in a year
Equivalent Dose to the Skin, averaged over 1 cm^2 of skin	500 mSv in a year	50 mSv in a year
Equivalent Dose to the Hands and Feet	500 mSv in a year	-

- These limits apply only to doses received above the normal local natural background radiation
- Dose limits do not apply to medical exposures
- National regulations may prescribe different mandantory dose limit values

ICRP/ICRU Publications

ICRP 60	1990	Recommendations for weighting factors
ICRU 51	1993	Definition of operational dose quantities
ICRP 74	1997	Definition of dose quantities in radiation protection
ICRP 103	2007	Protection Dose Quantities: new weighting factors and recommendation for protection limits
ICRP 110		Adult reference computational phantoms
ICRP 116	2010	New conversion coefficients based on ICRP 103
ICRP 118	2012	Recommendations for the lens of the eye

ICRP: http://www.icrp.org
ICRU: http://www.icru.org

European Commission, radiation protection series publications: *Technical Recommendations for Monitoring Individuals Occupationally Exposed to External Radiation*, RP 160. Free download: https://ec.europa.eu/energy/sites/ener/files/documents/160.pdf

Thank you very much!
Questions? Feedback?