Issues on Radiation Weighting Factor

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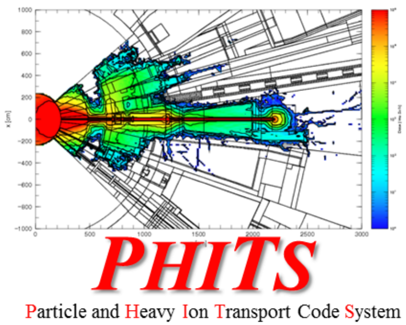
Who am I ?

Research Topics



- ✓ Development of the PHITS code*
- ✓ Its application to radiation biology and dosimetry

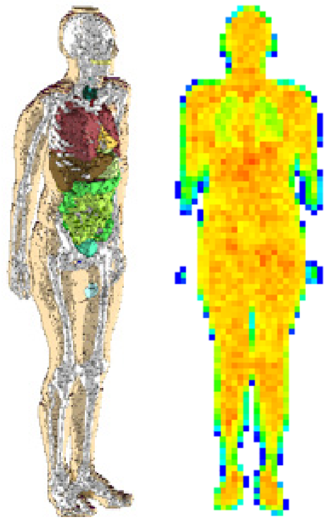
Contributions to ICRP

- ✓ Submit dose conversion coefficients calculated by PHITS to DOCAL → for ICRP116

Radiation weighting factor: w_R

- ✓ Evaluate dose conversion coefficients used in space dosimetry → as a co-author of ICRP123

Radiation quality factor: $Q(L)$ or Q_{NASA}



ICRP voxel phantom (ICRP110)

T.Sato et al. J. Nucl. Sci. Technol. (2013); http://phits.jaea.go.jp

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RBE & Quality Factor

Risk of radiation exposure depends not only on dose and dose rate but also characteristics of radiation causing the dose

Radiation Biology

RBE (Relative Biological Effectiveness): Failla and Henshaw (1931)

= Ratio of absorbed doses of two types of radiation that produce the same specified effect

Depends on dose, dose rate, biological endpoint etc.

Radiological Protection

Quality Factor: ICRU9 (1959)

= "weight" absorbed doses to obtain a common scale for all ionizing radiations

Enables comparison and addition of doses from different radiations

Values of RBE & QF are similar, but their concepts are different

History of Quality Factor

Report of the RBE committee of ICRP & ICRU (1963)

Discrete function of Linear Energy Transfer (LET) in water: QF

ICRP26 (1977)

Continuous function of LET: $Q(L)$

ICRP60 (1990)

Continuous function of LET: $Q(L)$

Form was revised based on Q(y)

ICRU40 (1986)

Continuous function of lineal energy, y, for d = 1um: $Q(y)$

Based on the production of dicentric chromosome of human lymphocyte

NASA/TP-2011-216155

Continuous function of LET & Z^*/β: Q_{NASA}

✓Z^*/β roughly represents the track structure of charged particle

Used in ICRP123

History of Radiation Weighting Factor

Problems of Quality Factor

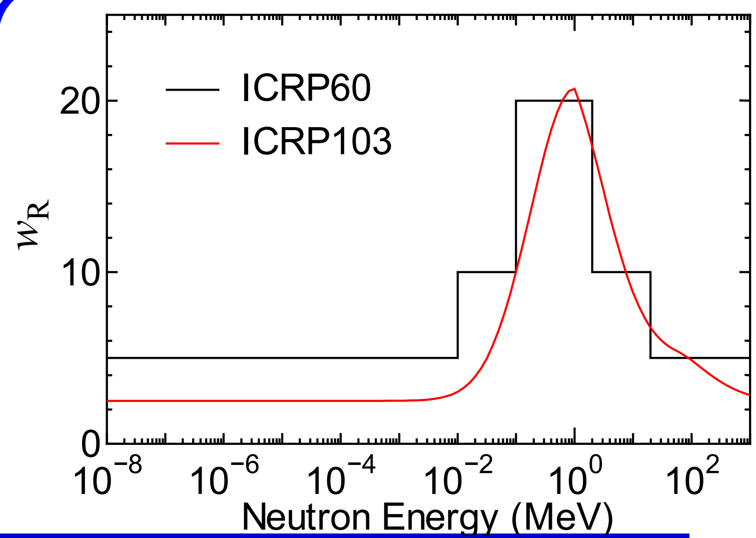
- ✓ Q is weighted on dose at a point → Factor to be weighted on organ dose
- ✓ Q is often interpreted to imply a spurious precision → More simple relation

ICRP60 (1990)

- ✓ Radiation weighting factor was introduced to be weighted on organ dose
- ✓ Q(L) remains only to be weighted on dose at a point, such as H*(10)

Numerical values of w_R

	ICRP60	ICRP103
Photon, e^-, μ	1	1
Proton	5	2
α, heavy nuclei	20	20
Neutron	Step	Continuous



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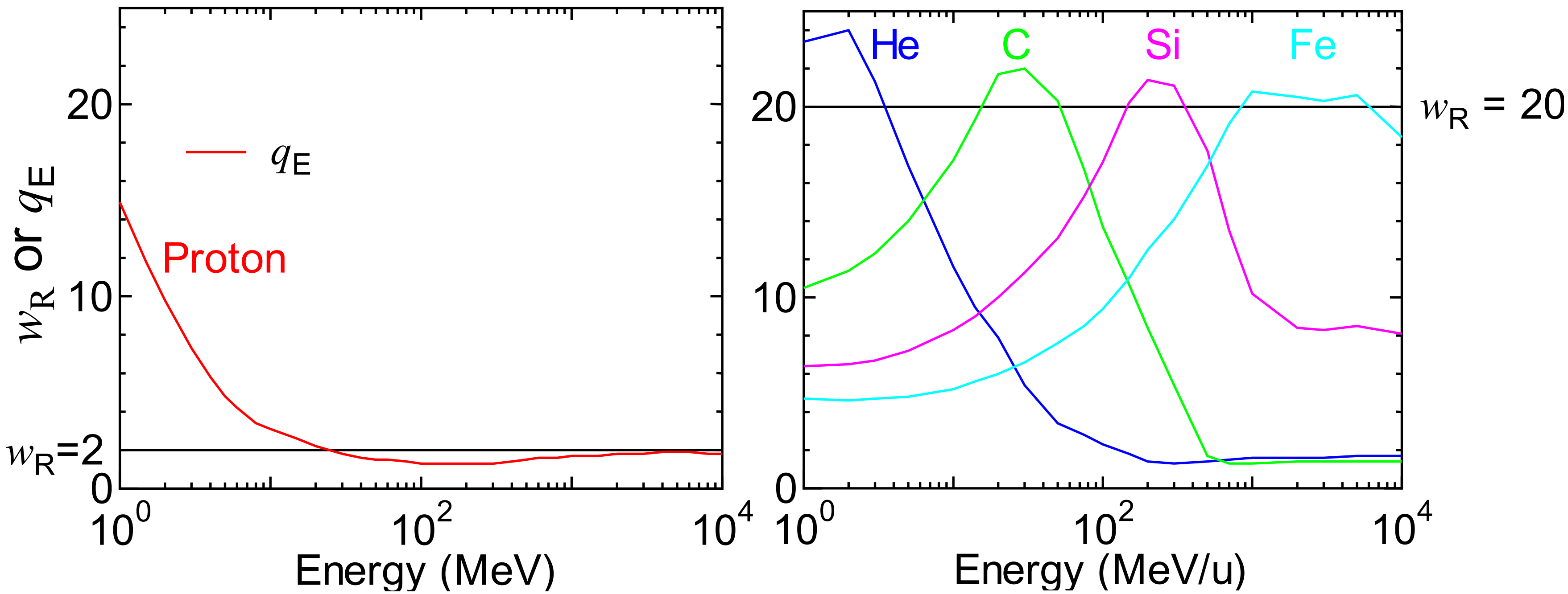
This simplified concept works well for radiological protection of public, but induces some problems in certain situations

Inconsistency between w_R and $Q(L)$

- ✓ Numerical coherency between w_R and $Q(L)$ must be established
- ✓ Dependence of RBE on charged particle energy is considered only in $Q(L)$



Comparison between w_R & the effective quality factor, q_E

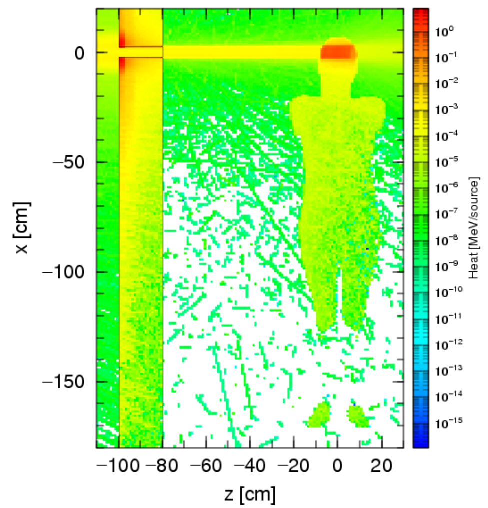
(data are taken from ICRP123)

Ignorance of this energy dependence is not acceptable for space dosimetry, Choice of w_R is quite reasonable from the conservative viewpoint

Incident Particle Determines All

✓ w_R is assigned to incident particle type regardless of exposure situation
→ Problems for non-uniform irradiation

Risk Estimation of Second Cancer for Charged Particle Therapy



Example of dose inside patient for carbon-ion therapy

Determination of the equivalent dose by strictly following the definition of w_R

✓ H = D x 2 for proton therapy
✓ H = D x 20 for carbon-ion therapy

Secondary neutron is the dominant particle contributing to organ dose far from the target

✓ **Effective dose should NOT be used in the personal risk estimation**
✓ **Only ICRP can define a new quantity used for that purpose**

It is worthwhile to consider a future concept of quality factor now!

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Candidates for the Physical Index

Name	Symbol	Track structure	Stochastic nature of dose (Single hit)	Stochastic nature of dose (Multiple hit)
Unrestricted LET (ICRP26, 60)	L_{∞}	X	X	X
Restricted LET	L_{OOeV}	O	X	X
Effective charge / Speed (NASA-TP2011)	Z^*/β	O	X	X
Lineal energy (ICRU40)	y	O	O	X
Specific energy	z	O	O	O

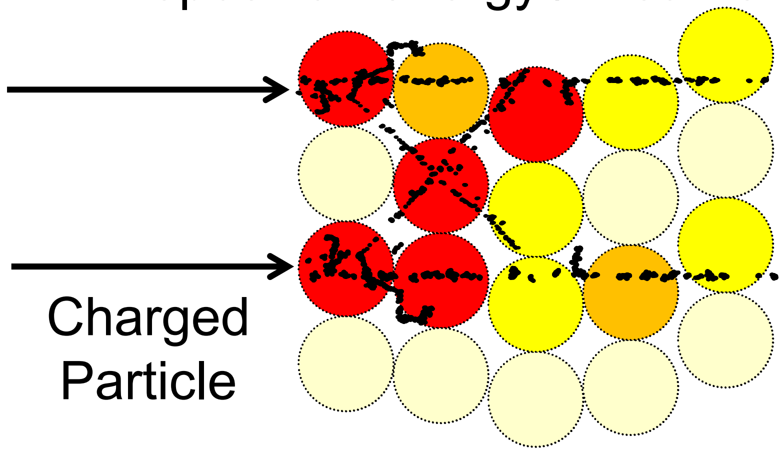
"Microdosimetric Quantity" defined in ICRU36

Specific Energy (z) & Lineal Energy (y)

Radiation Quality ← Deposition energy in microscopic site → **average** → Absorbed dose D(Gy)

Deposition energy in microscopic site → **density** → LET (keV/μm)

- Specific Energy *z* (Gy): Multiple hit
  Deposition energy / Mass
- Lineal Energy *y* (keV/μm):
  Deposition energy / Mean chord length



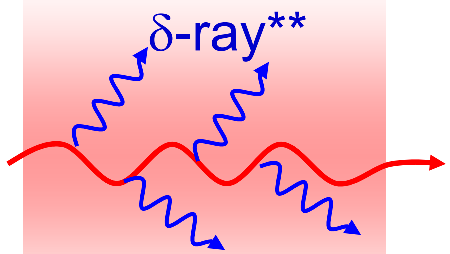
Concept of z & y and example of track structure

LET (keV/μm)

*Mean transfer energy within a certain distance

Density : **High**

Low-energy radiation



Density : **Low**

High-energy radiation

*excluding radiative energy loss

h-energy knock-out electron

- Complicated track structure due to δ-ray production
- Stochastic nature of doses in microscopic sites

Why microdosimetric quantities are not frequently used as the index?

Answer is…
Their PDs were difficult to be evaluated

Our Original Method for Calculating PDs

Particle transport simulation in DNA & cellular scales (Track Structure)

Mathematical Function

Particle transport simulation in human body scale (PHITS)

Enables PHITS to be capable of calculating PDs by single-hit radiation

Poisson statistics & convolution integral

Single-hit PDs → Multiple-hit PDs

Sato et al. Radiat. Res. (2009); Sato & Furusawa, Radiat. Res. (2012); Sato & Hamada, PLOS ONE (2014)

PDs of y & z can be calculated for any exposure situation!!

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Advantages

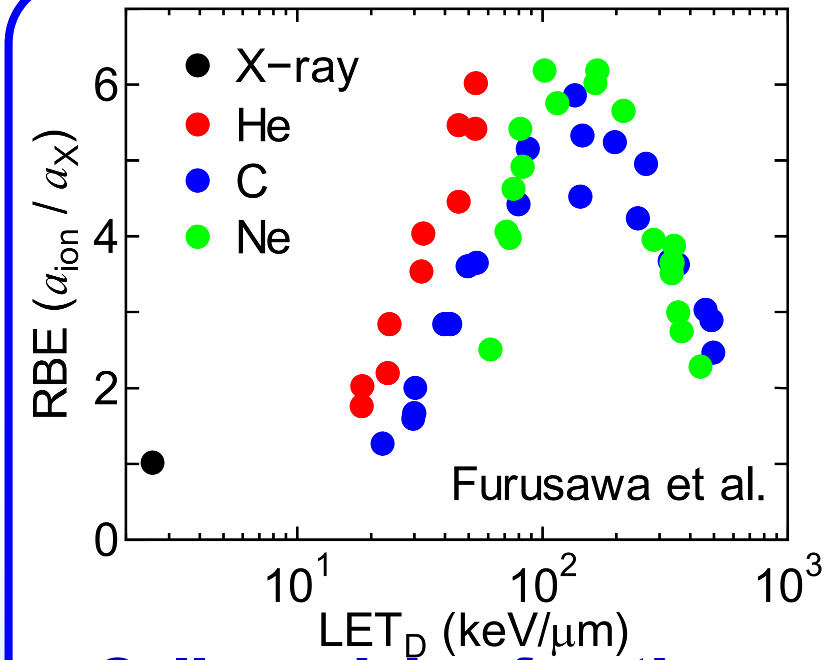
It can consider...

1. Difference in RBE among ion species at the same LET
   → track structure
2. Difference in RBE among photons of different energies
   → track structure
3. Dose effect due to stochastic variation of absorbed doses in each cell
   → stochastic nature for multiple-hit radiation, $Q(z)$
4. Recent radiobiological findings such as non-targeted effects
   → stochastic nature for multiple-hit radiation, $Q(z)$

Consideration on Track Structure

✓ Lower Z particles have higher RBE than higher Z particles at the same LET
✓ Low-energy X rays have higher RBE than γ-rays

Due to the difference of track structure



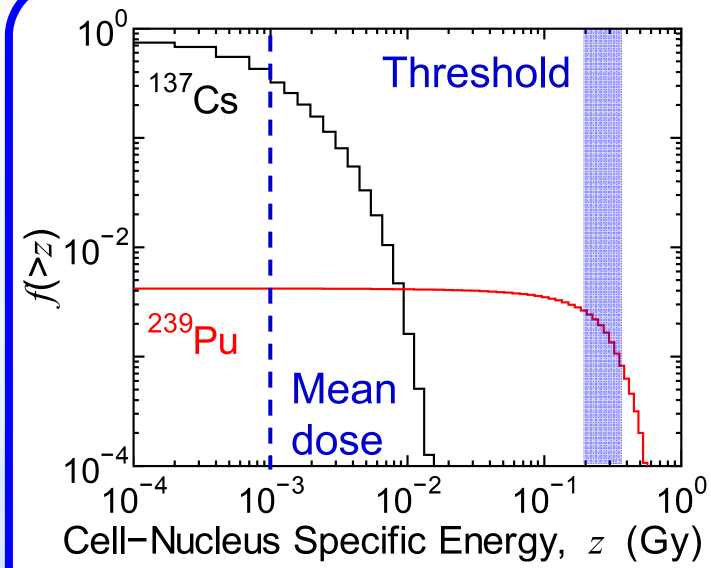
Cell surviving fractions

Furusawa et al. Radiat. Res. (2000)

Track structure has already been taken into account in $Q(y)$ & Q_{NASA} as well as treatment planning of carbon-ion therapy

Consideration on Stochastic Nature

- ✓ Related not only to QF but also DDREF
- ✓ Extensively discussed more than 50 years (e.g. ICRP103 annex B.2)



Probability of cell having its nucleus dose above z for internal exposure of ^{137}Cs and ^{239}Pu with D = 1 mGy

How this variance influences the risk?

Cellular response non-linear to dose

$$R(D) \neq \int R(z) f(z) dz$$

- ✓ $R(D)$: Risk estimated from mean dose D
- ✓ $R(z)$: Risk of each cell with nucleus dose z
- ✓ $f(z)$: PD of cell-nucleus specific energy z

Non-Targeted Effect

- ✓ Non-targeted cells exhibit some radiation effects due to irradiation of surrounding cell
- ✓ Only small fraction of cells are irradiated by dose above a certain threshold

NTE would be observed only in Pu exposure

- ✓ **The variance becomes larger for high-LET and low-dose irradiation**
- ✓ **Stochastic nature must be considered in the future QF and DDREF**

Disadvantages

1. The concept & the numerical relationship of the radiation quality factor would not be simple
   Not directly results in abandoning the simplicity of the radiological protection system, because QF is mainly used for calculating DCC
2. Definitions of *z* and *y* are hard to understand for non-specialist of microdosimetry
   As you may feel now…
3. Target sizes related to the radiation exposure risk must be determined
   Big challenge of radiation research. What is the target?
   → DNA, chromatin, chromosome, cell nucleus, cell, or organ…
4. Biological experimental data are rarely analyzed as a function of *z* or *y*, due to the difficulty of their evaluation
   Closer communication between radiobiologist and dosimetrist is the key to overcome this disadvantage

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2. Physical Index Suit for Expressing New Quality Factor
3. Features of Microdosimetry-Based Quality Factor
4. Summary

Summary

Issues on Radiation Weighting Factor

- ✓ The simplified concept of radiation weighting factor works well for radiological protection of public
- ✓ It cannot be used in space dosimetry, and should not be used in the personal risk estimation

There are needs to define a new quality factor !

Features of Microdosimetry-Based Quality Factor

- ✓ It can consider both track structure & stochastic nature of doses
- ✓ Concept would not be simple as it is
- ✓ Progresses on radiation research are necessary to determine its numerical relationship & appropriate target sizes

Recent radiobiological findings can be included in the radiological protection system → this feature can accelerate radiation research

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Collaborators

PHITS development

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