Before, Berkeley and Beyond

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Part I: Before and Berkeley

- Before Berkeley: 1895—1932
- The *Annus Mirabilis*: 1932
- Berkeley: 1932—1970
Before Berkeley
1895—1932

- 1895: Discovery of x-rays—Roentgen
- 1897: Discovery of radium—Madame Curie
- Application of x-rays predominantly to diagnosis: low-energy photons
- Strong connection between medical applications of radiation and protection set future focus for advisory bodies
Annus Mirabilis
1932

- “Splitting the atom”: Cockcroft and Walton
- First cyclotron: Lawrence and Livingston
- Discovery of the neutron: Chadwick
- Discovery of the positron: Dirac 1930, Anderson 1932
Splitting the Atom
The First Cyclotron
Berkeley
1932—1942

- 1933: Artificial radioactivity—Fermi et al., Joliot-Curie
- 1935:
  - Neutron RBE ~10—John Lawrence et al.
  - Neutron limit 0.01 R/day—Ernest Lawrence
  - Radio-sodium, radio-phosphorus—Hamilton
- 1936:
  - Neutron radiotherapy—Stone et al.
  - Neutron radiobiology—Aebersold et al.
  - Metabolism of radionuclides—Hamilton et al.
- 1938: Radioactivity of tritium—Alvarez and Cornig
- 1940 — 42: First transuranic elements—McMillan and Seaborg
- 1942: Self-sustaining neutron chain reaction—Fermi et al.
Birth of Nuclear Medicine
1935

Joseph Hamilton
drinking
radio-sodium
The Discovery of Neptunium
1940

Ed McMillan
Berkeley during the Postwar Period

- Professional accelerator health physics department
- The “Moyer Model”
- Radiation transport studies: “shielding experiments”
- Fluence-based neutron dosimetry
LBL Health Physics Personalities

Burton J. Moyer, chairman of Cal physics department (1962)
LBL Health Physics
Personalities

From left:
Joe McCaslin,
Lloyd Stephens,
Wade Patterson,
Al Smith
(1966)
Moyer’s Bevatron Roof Shielding
1962
The Moyer Model
Bevatron Shielding Experiment
1964
Neutron Attenuation vs. Energy and Angle

![Graphs showing neutron attenuation versus energy and angle](image-url)
Fluence-Based Dosimetry

- Fluence-based system has many advantages:
  - Fluence may be measured
  - Widely used at particle accelerators
  - Fluence is more fundamental than absorbed dose
  - Fluence data are stable *cf.* current biological data
  - Fluence data may be used to calculate physical data required by biologists
  - Recommended by ICRU Committee on the Practical Evaluation of Dose Equivalent: 1980
Emphasis placed on adequate determination of differential energy spectrum of fluence, $\frac{d\phi}{dE}$, and total neutron fluence, $\Phi$:

$$\Phi = \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{d\phi}{dE} dE$$

where $E_{\text{min}}$ and $E_{\text{max}}$ are spectrum bounds.
Fluence-Based Dosimetry (cont.)

Radiation protection quantities, $H$, are determined using fluence-to-dose conversion coefficients, $g(E)$:

$$H = \int_{E_{\text{min}}}^{E_{\text{max}}} g(E) \left( \frac{d\phi}{dE} \right) dE$$
Neutron Conversion Coefficients

Conversion Coefficient (pSv Cm²)

Neutron Energy (MeV)

- MADE, NBS 63 (1957)
- MADE, RHT (1965)
- MADE, ICRP 21 (1971)
- MADE, NCRP 38 (1971)
- MADE & H*(10), ICRP 51 (1987)
- E, ICRP 74 (1995)
- E, Ferrari et al. (1997)
- E, Yoshizawa et al. (1998)
- E, Bozkurt et al. (2001)
“To retain respect for sausages and laws, one must not watch them in the making.”

Prince Otto von Bismarck 1815—1898
Part 2: High LETs and High Energies Are Different!

- The importance of high-LET radiations
- Goals for an “ideal” system of dosimetry
- Dosimetry systems based on absorbed dose versus fluence
- Radiation weighting
- $w_R$ and its concomitant problems
- Suggested solutions
- New ICRP recommendations
Importance of High-LET Radiations

- Air-crew exposures among highest “occupational exposures”
- Fraction of workers exposed to neutrons or internal emitters roughly equal (~15%)
- Future increased nuclear programs may increase exposure to high-LET radiations
- At low doses, high-LET exposures may be more biologically significant
- Space travel
Goals for an “Ideal” System of Dosimetry

- Universal: applying to all radiations and energies
- Integrated: independent of radiation origin (outside or inside the body)
- Rational and rigorous: consistent with mathematical logic and physical laws
- Stable: infrequent changes in names and symbols of concepts
- Unambiguous: standard set in determinable (physical) quantities thus making them measurable, giving rise to
- Identical “protection” and “operational” quantities
Photon Dosimetry Based on Modified Absorbed Dose

- “Absorbed dose is the physical quantity underlying the whole of operational protection and the recommendations of ICRP”
- And later, “. . . Both these quantities (dose equivalent and effective dose equivalent) are nothing more than weighted (modified) absorbed doses” – John Dunster 1988
- But the difficulty lies with radiation weighting – RHT 2008
Difficulty with Radiation Weighting: Photons

- Epidemiological data available for the estimation of risk
- Interactions in tissue produce low-LET radiations
- Radiation weighting problem defined away
- Radiation weighting factor is assumed and defined to be 1 at all energies
- This “solution” may be convenient but it is poor biology and poor physics
Difficulty with Radiation Weighting: Neutrons

- No epidemiological data available for neutrons
- Risk estimates obtained from cellular and small animal RBE data
- Interactions in tissue produce both low- and high-LET radiations
- Radiation weighting very important
- RBEs sometimes much greater than 1
- Extrapolation from mouse to man fraught with difficulty
- Energy regime is wide
Experimental Curves of RBE vs. LET: Mammalian Cells

[Graph showing experimental curves of RBE vs. LET for different energies and ions, including data points and error bars.]
ICRP $Q(L)$-$L$ Functions, Old and New: 1969 and 1990

![Graph showing $Q(L)$ vs. Linear energy transfer (keV/μm)]
Extrapolation of RBE Mouse Data to Homo Sapiens
Evolution of Modified Absorbed Dose

Before ICRP Publication 60
- Absorbed dose circa 1940
- RBE dose 1948
- Dose equivalent, $H$ 1965
- MADE 1973
- Effective dose equivalent, $H_E$ 1977,1980
- Dose equivalent indexes 1980

After ICRP Publication 60
- Ambient dose equivalent, $H^*(d)$ 1985
- Effective dose, $E$ 1991
Evolution of Radiation Weighting

Before ICRP Publication 60
- 1933 RBE
- 1968 Quality factor, $Q$
- 1969, 1971 $Q$ as a function of LET, $Q(L)$
- 1971 Mean quality factor, $\overline{Q}$
- 1977, 1980 Effective dose equivalent, $H_E$ and $\overline{Q}$

After ICRP Publication 60
- 1990 Effective dose, $E$ and $w_R$
Difference between Effective Dose Equivalent and Effective Dose

\[
\bar{Q} = \frac{\int Q(L)\left(\frac{dD}{dL}\right)dL}{\int \left(\frac{dD}{dL}\right)dL}
\]

\[
H_E = \sum_T w_T H_T = \sum_T w_T \bar{Q}_T \bar{D}_T
\]

\[
E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R \bar{D}_{T,R}
\]
Triumph and Tragedy

Triumph

- 1933—1980: Steady progress toward the “ideal”
- 1977—1980: Effective dose equivalent almost perfected

Tragedy

- 1985—1993: Progress steadily dismantled
  - 1985 Paris meeting
  - 1991 ICRP Publication 60
  - 2003 ICRP Publication 92
Most Important Changes Made to Radiation Weighting

- ICRP Paris meeting (1985) recommended “an increase in . . . the permitted approximation [of Q] . . . from 10 to 20.”
- Subsequently ICRP Publication 51 applied this increase to all energies
- ICRP Publication 60 introduced
  - New function for $Q(L)$
  - New quantity: effective dose
  - New system of radiation weighting: $\overline{Q}$ replaced by $w_R$
- ICRP Publication 92: essentially in defense of Publication 60
Neutron Conversion Coefficients
Stable against Change

Fluence-to-Dose Equivalent Conversion Coefficients (pSv \cdot cm^2)

Neutron Energy (MeV)
ICRP Publication 60 Introduced New $Q(L)$-$L$ Function

![Graph showing $Q(L)$ vs. Linear energy transfer (keV/μm)]
Goals for an “Ideal” System of Dosimetry

- Universal: applying to all radiations and energies
- Integrated: independent of radiation origin (outside or inside the body)
- Rational and rigorous: consistent with mathematical logic and physical laws
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- Identical “protection” and “operational” quantities
What is $w_R$ for Neutrons?

- $w_R$ is $\bar{Q}$ for ambient dose equivalent, $H^*(10)$
- Depth $d = 10$ mm, ICRU sphere, expanded and aligned radiation field
- Defined values presented as a histogram
- “Approximate” values given by
  \[ w_R = 5 + 17 \exp\left\{-\frac{\ln(2E)^2}{6}\right\} \]
- Calculated using a $Q(L)$ function recommended but “damned with faint praise” by ICRP 60
Problems with $w_R$

- Defined in detail only for neutrons
- Not applicable to internal dosimetry
- Phantom choice inapt: ICRU sphere, not anthropoid phantom
- Calculated using $Q(L)$ function recommended by ICRP 60
- Values for $w_R = 5$ for neutrons < 10 keV and > 20 MeV are implausible
- Value of $w_R = 20$ for neutrons of 100 keV is controversial
More Problems with $w_R$

Values of $\bar{Q}_T$ and $w_R$ not in concordance

$H_{E - AP}$ 100 keV $\bar{Q} = 7.1$

- Testes $\bar{Q} = 8.8$
- Ovaries $\bar{Q} = 1.3$
- Remainder $\bar{Q} = 2.4$
- Bone S. $\bar{Q} = 1.2$
- Thyroid $\bar{Q} = 8.0$
- Lung $\bar{Q} = 2.8$
- Breast $\bar{Q} = 3.9$
- Bone M. $\bar{Q} = 8.8$

$E - AP$ 100 keV $w_R = 16$

- Ovaries
- Remainder
- Thyroid
- Lung
- Breast
- Others
- Bone marrow
- Testes
- Breast
ICRP Publication 92 Analysis of $w_R$
ICRP Publication 92’s Suggested Correction

![Graph showing the comparison between the current discontinuous convention and the proposed $w_R$.](image-url)
Difficulties with Publication 92’s Suggested Corrections

- Designed to retain the value $w_R = 20$ at 1 MeV by the equation
  \[ w_R = 1 + 1.6 \left( q_E - 1 \right) \]

- Consequences
  - $w_R \equiv q_E$ at energies < about 20 keV
  - $w_R \neq q_E$ at energies > 20 keV
  - $w_R \approx 1.6 q_E$ at 1 MeV
  - At energies > about 100 MeV, $w_R = 2$ for protons is incompatible with $w_R = 5$ for neutrons
Suggestions for Universality and Integration

Adopt a fluence-based system of dosimetry

☐ “More fundamental” than absorbed dose
☐ Applicable to all radiations
☐ Widely used at particle accelerators
☐ Use of $\bar{Q}$ integrates internal and external dosimetry
Suggestions for Radiation Weighting

Is concept of \( Q(L) - L \) function still scientifically valid?

If yes,

- Determine current best estimate and uncertainty
- Review biology and physics of extrapolating RBE data from small animals to humans
- Determine whether neutron RBE for mice depends on radiation field
Suggestions for “Measurability”

- Define only protection quantities
- Adopt fluence-based dosimetry scheme
- Recognize that measurement techniques are best provided by dosimetrists
- Define and select standard anthropoid phantoms and transport codes
- Abandon effective dose; revert to effective dose equivalent
Suggestions to Advisory Bodies

- Change recommendations only when new scientific data warrant
- Examine and understand impact of new recommendations before promulgation and implementation
- Scrutinize text for concordance
- Cease frequent changes in nomenclature
- Recruit to committees young minds that are current in theoretical and practical methods
ICRP Rebuttal: On Ambiguity

“ICRP, for good reasons, has been rather relaxed with its definition so that the calculated magnitude of effective dose is somewhat ambiguous. However, this is in line with the Commission’s generous, and appropriate, recommendations on the needed accuracy.”

Lindell 2001
“Radical simplification of $w_R$ seems impracticable . . . It would tend to force tightening of [all] the dose limits . . . If the current value of 20 for fission neutrons were reduced to 10, this would . . . amount to a relaxation of limits for neutron exposure, which may meet strong objections and . . . generate pressure to offset the change by a decrease of the effective dose limits . . . [applying] to all radiations . . .”

ICRP 92, Paragraph 259
New ICRP Recommendations for 2007/8

- In 2001 ICRP announced it would prepare revised recommendations to be published in about 2005
- Since then ICRP has been extremely conscientious in seeking public comment on its recommendations and drafts
- In 2004 the author was invited to prepare a critique of ICRP 92
- In March 2007 ICRP approved its new recommendations
- At the time out of preparing this lecture (December 2007) new recommendations had not been published
What Might We Expect?

- Some small changes but no substantial movement on fundamental issues
- $w_R$ (for neutrons) will be retained but a continuous function defined
- Values of $w_R$ at low and high energies will be $\approx 2$
- The system will be anchored to $w_R \approx 20$ at 1 MeV
- Fluence may be mentioned ambiguously
- No “official” acceptance of a fluence based dosimetric system
“I know that most men, including those at ease with problems of the greatest complexity, can seldom accept even the simplest and most obvious truth if it be such as would oblige them to admit the falsity of conclusions which they delighted in explaining to colleagues, which they have proudly taught to others, and which they have woven, thread by thread, into the fabric of their lives.”

Attributed to Count Leo Tolstoy
“So long, it’s been good to know ya!”

Woody Guthrie 1912—1967