The Art of Developing Practical Dosimetry

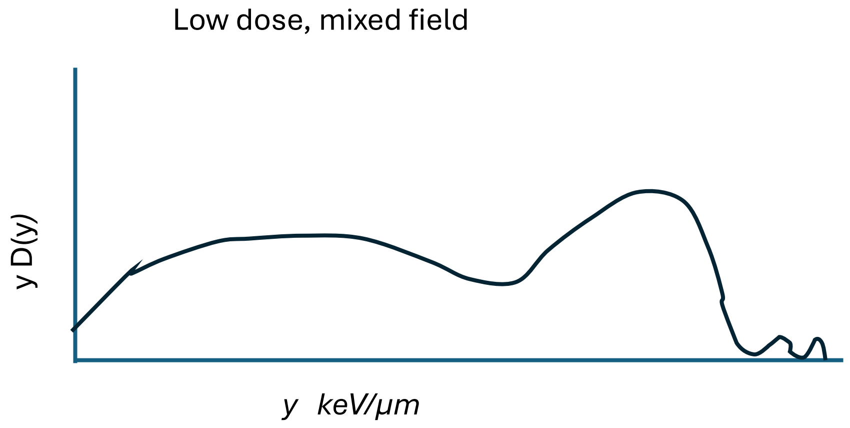
Les Braby

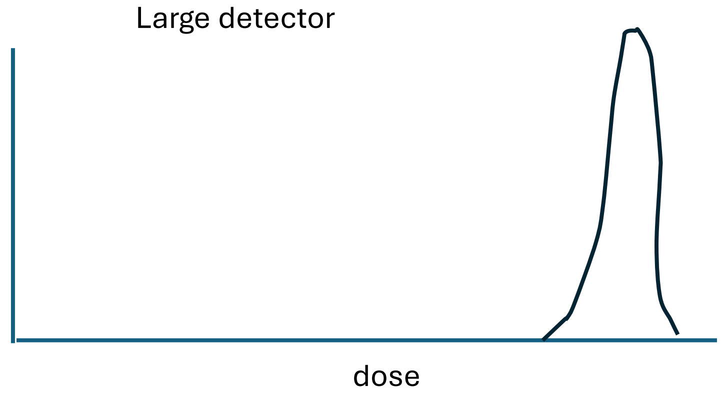
Texas A&M, retired

The fundamentals

- We need the energy deposited in relevant biological targets
- Nearly all detectors convert indirectly ionizing radiation to directly ionizing particles
- Development of absorbed dose and LET, was motivated by medical (therapeutic) applications – high dose
- Those quantities are expectation values, the average value at a point in space
- Radiation tracks and interactions occur randomly; the energy deposited in a small volume of tissue is unique

- The probability of an amount of energy deposited is described by the probability density function (PDF)
- At low dose the PDF is very broad, from a few eV to over 100,000eV
- At higher dose the mean of the PDF increases and the relative width decreases
- In a large detector the number of events is proportional to the detector area and the relative variance is typically less than 1%





Measuring absorbed dose in tissue

- Since cross sections for producing charged particles and for energy deposition by charged particles are dependent on atomic composition, the ideal detector is tissue equivalent
- Use of other detector materials requires energy dependent conversion from energy deposition in the detector material to energy deposition in tissue

Radiation quality

- The effect depends on the process leading to the damage as well as the physical nature of the energy deposition
- There is no clear indication of a physical property of radiation that will serve to predict biological effectiveness (radiation quality)
- health physics traditionally uses LET while charged particle beam therapy uses lineal energy or the local dose
  - LET can be estimated from the PDF of energy deposited in a thin (small) detector
  - local dose is calculated from particle mass, charge, and velocity, so it requires measurement of charged particle spectral radiance,
  - lineal energy can be measured directly for a chosen target volume, usually a 1 or 2 micrometer diameter sphere of tissue

Dose rate

- Since dose rate and radiation quality vary with altitude, geographic location, and space weather - evaluate both dose rate and radiation quality as functions of time
- Temporal resolution and dose rate determine the dosimeter sensitivity required
- Selection or design of a dosimetry system requires compromise between accuracy, sensitivity, type of radiation quality description, size/weight of instrument, and data management

- Passive dosimeters do not provide dose rate, just total dose since last read, so will not be considered further

Examples of detector types

TE ion chambers

- Accuracy is as good as the TE material's simulation of the attenuation coefficients and stopping powers of real tissue, generally better than 5%
- Sensitivity depends on volume, gas pressure, and electronic gain. For a 2 liter detector at 760 torr 10^{-14} amp = 0.14 nGy/s
- No discrimination of radiation quality

Scintillators

- Density over 1000 that of air results in much smaller detector
- Requires high gain photon detector, typically a photomultiplier tube
- Can be used in current mode, giving dose rate, or in pulse mode giving dose rate and data on radiation spectrum
- Atomic composition requires converting absorbed dose in scintillator to absorbed dose in tissue
- Conversion factor is generally energy dependent requiring knowledge (or assumptions) of incident photon spectrum
- Sensitivity to neutrons depends on hydrogen content – organic scintillator with pulse shape discrimination electronics can identify the charged particle (electron or proton) producing most events, giving some information of radiation quality

Thick semiconductors

- Operate similar to chambers, collecting electrons and holes
- Density around 3 g/cm^3 and *w* about 1/10 of TE gas so detector can be very small
- Sensitive to photons and directly ionizing particles but not neutrons
- Absorbed dose in Si (or other semiconductor) requires energy dependent conversion to absorbed dose in tissue

Thin semiconductors

- Operate as ΔE detector for primary and secondary charged particles and as solid state ion chambers
- Sensitivity is proportional to detector area, which determines the number of particles detected in a radiation environment
- Use TE cover to provide neutron and photon sensitivity
- Determination of dE/dx, an estimate of LET, requires measurement of path length through the semiconductor
- Electronic noise prevents measurements of low energy deposition events – best preamp noise limits to pulses larger than 300 electrons – about 1 keV energy deposited

^{3}He and other neutron detectors

- Usually used as part of a suite of detectors to determine fluence as a function of energy for indirectly ionizing radiations

Lineal energy dosimeter

- Essentially a TE ion chamber operating at low pressure so that ρd equals a few micrometers in unit density tissue
- Records individual energy deposition events and adds them up to get total energy deposited and absorbed dose in tissue

- Electronic noise and gas gain determine minimum energy deposition that can be detected, often 2 or 3 ion pairs in the volume. Determination of absorbed dose requires estimation of the number of small events that could not be detected due to noise.
- Accuracy like TE ion chamber but with additional error due to estimated number of small events. Better than 10% with very low noise electronics.
- Sensitivity proportional to cross sectional area of detector
- Measures probability density function of lineal energy for all charged particles of any type

There is no single answer to the question of the best detector

The answer must be based on evaluation of the importance of each of the factors

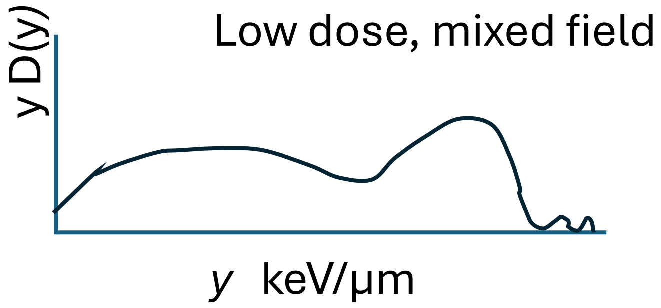
- accuracy
- sensitivity
- type of radiation quality description
- size/weight of instrument
- data management

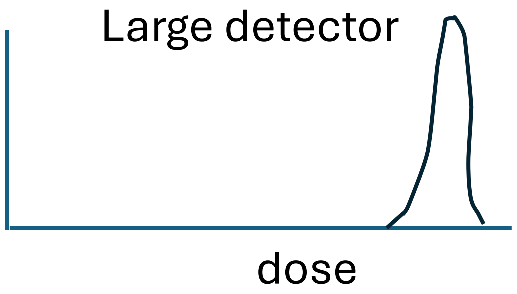
For example

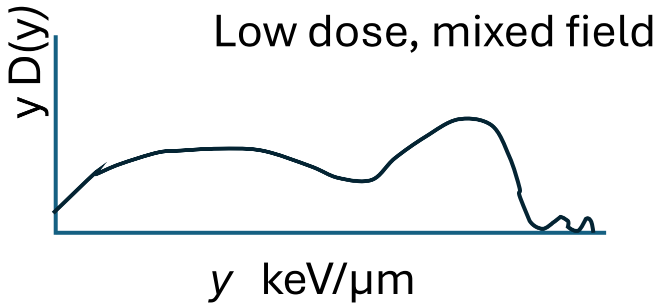
- In radiation therapy tissue equivalent ion chambers are used because accuracy of absorbed dose in tissue is most important – their quality control procedures maintain a constant radiation quality, so they do not have to measure it
- Evaluation of the radiation environment in nuclear power plant control rooms was done using a suite of proportional counters, scintillators, and solid state detectors which filled several large trunks. The evaluation of absorbed dose as a function of particle type and energy was critical, but size and weight were only a minor concern.

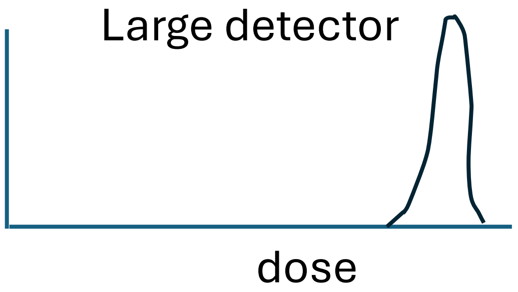
- NASA used lineal energy dosimeters on the space shuttle and ISS to determine the absorbed dose in tissue and the PDF of lineal energy as functions of the location within the vehicle and the space weather. Having refined their understanding of the radiation environment they have switched to smaller but less sensitive thin semiconductor detectors with track length detection to monitor for any changes in the environment.
- Lineal energy dosimeters using 5 inch diameter TE proportional counters fitted into carry-on suitcases were used by NIOSH to evaluate absorbed dose in tissue and the PDF of lineal energy as a function of geographic location and altitude.

- The art is in adequately evaluating the needs of the specific application, without letting the available instruments bias the evaluation
- Once the needs are understood one or more suitable measurement methods will be evident


Low dose, mixed field
y D(y)
y keV/μm


Large detector
dose


Low dose, mixed field
y D(y)
y keV/μm


Large detector
dose