Challenges of Personnel Dosimetry at Accelerators

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Outline

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- Accelerator Radiation Fields
- Radiation Detectors for Personal Dosimetry
- Examples of Personal Dosimeters
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- Calibration and Traceability
- Quality Assurance and Documentation
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INTRODUCTION

- **Is it personnel dosimetry – Or personal dosimetry?**
- **The term personal makes grammatical sense, i.e.**
  a worker’s dosimeter is a personal or individual dosimeter
- **ICRU, and N13.11 use the term personal dose equivalent**, $H_p(d)$
- **Despite my being Editor of RPD, I won’t argue**
  spelling of dosimeter vs. doseimeter
What is an Accelerator?

- NCRP 144 “Radiation Protection for Particle Accelerator Facilities” defines an accelerator by its ability to initiate nuclear reactions.

- I take a broader view, more like NCRP 51, and include any radiation generating device that imparts kinetic energy to particulate radiation.

- I believe an x-ray machine is an accelerator, so is a linac used to disinfest foodstuffs or sterilize band-aids (energies may be required to be low so as to not produce nuclear reactions).
Van de Graaffs, tandems, cyclotrons, hospital linear accelerators, synchrotrons, heavy-ion linacs and colliders are clearly accelerators.

But low energy radiation processing accelerators are numerous and used to cure aerospace composites, produce shrink-wrap packaging, degenerate Teflon into powder for lubricants, sterilize disposable medical products, etc.

Accidents at these devices are rare but usually major – personal dosimetry is definitely needed.
Radiation fields at small accelerators are “generally” limited to low-LET radiations – but

Food irradiation accelerators are limited to 10 MeV for electrons, 7 MeV for bremms. from Ta, Au targets, 5 MeV for other targets

Medical-product-sterilizing linacs run in similar energy ranges and dose rates are huge

There is restricted access to the direct beam – but, maintenance must be performed, and sometimes things go badly
Low Energy Accelerators

Radiation Sterilization Facility

Low Energy Accelerator Dosimetry

- Personal dosimeters need to cover a wide range of absorbed doses and dose rates – from protection levels to accident levels
- Alarming electronic dosimeters are needed for an immediate warning of high dose rates
- Unfortunately, dosimetry may also be carried out using wrist watch jewels, teeth or blood… Maybe *post mortem*
Moving on to happier thoughts

- Most of our discussion will focus on dosimetry for larger accelerators.
- Primary beam energies can range to many GeV, access to areas near primary beam lines restricted.
- Radiation fields in most workplaces contain a mixture of high- and low-LET radiation that has passed through shielding.
- Predominately photons and neutrons, perhaps some muons.
Quantities and Units

- Why discuss quantities and units? Boring!
  Answer, We need to know what are we measuring

- ICRP 60 quantities in revision of 10 CFR 835.
  Another good reason to discuss quantities and units

- In the 2007 ICRP Publication, some recommendations have changed, but protection quantities remain basically unchanged

- What do we have right now?

- Let’s Get Down to Basics –
Starting with the basics -

- One – a number such that, for any number A, A times one is A (ISO 8485, 1989)
- Two –
Starting with the basics -

- One – a number such that, for any number A, A times one is A (ISO 8485, 1989)
- Two – *Anybody want to take a guess?*
Starting with the basics -

- One – a number such that, for any number A, A times one is A
- Two – one plus one (ISO 8485, 1989)
Starting with the basics -

- One – a number such that, for any number A, A times one is A
- Two – one plus one (ISO 8485,1989)

OK – enough frivolity, back to work!
Quantities, Units..What’s the Difference?

- A **quantity** is the property of a phenomenon, body, or substance, to which a magnitude can be assigned. An example of a quantity is absorbed dose.

- A **unit** is a standardized measure or amount used to express the magnitude of a quantity, and defined and adopted by convention.
Units have conventionally assigned names and symbols (but not all have names).

The special name for the unit of absorbed dose is gray, with a lower case g.

The symbol for the unit is Gy, and the plural of the unit’s name is also gray, with no following s.

And, what’s up with standards?

A standard is a material, object, or phenomenon which embodies a unit.
When is a standard not a standard?

Standard

?

Standard

En français: (un étalon) (une norme)
Some Rules of the Game

- A definition of a quantity taken from a document such as an ICRU Report, should be exactly as it appears in the original source such as ICRU 51 and 60 (see following slides).

- Some definitions may not be absolutely clear and may need additional explanation. This should be done in a note.

- For some examples see ICRU Report 66 on Neutron Dosimetry.
Radiometric Quantities

- **Fluence**, $\Phi$, is the quotient of $dN$ by $da$, where $dN$ is the number of particles incident on a sphere of cross-sectional area $da$, thus

$$\Phi = \frac{dN}{da}$$

Unit is m$^{-2}$ (cm$^{-2}$ also used) **no name**

- **Fluence rate**, or flux density, $\dot{\Phi}$, is the quotient of $d\Phi$ by $dt$, where $d\Phi$ is the increment of fluence in the time interval $dt$, thus

$$\dot{\Phi} = \frac{d\Phi}{dt} = \frac{d^2\Phi}{da \, dt}$$

Unit is m$^{-2}$ s$^{-1}$ (cm$^{-2}$ s$^{-1}$ also used)
**Dosimetric Quantities**

- **Kerma**, $K = \frac{dE_{tr}}{dm}$, where $dE_{tr}$ is sum of initial kinetic energies of charged particles liberated by uncharged particles in mass $dm$ of material.

- **Absorbed dose**, $D = \frac{d\bar{\varepsilon}}{dm}$, where $\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass $dm$.

Unit for both is J kg$^{-1}$, special name gray (Gy).
Kerma and Absorbed Dose
(Indirectly Ionizing Radiations)
Energy Deposition and Transfer

- **Linear energy transfer (LET)** or linear collision stopping power of a material for a charged particle is \( L = \frac{dE}{dl} \), where \( dE \) is the mean energy lost by the particle, due to collisions with electrons, in traversing a distance \( dl \)

- **Lineal energy** is the quotient of \( \varepsilon_s \) by \( l \), where \( \varepsilon_s \) is the energy imparted to the matter in a given volume by a single (energy deposition) event and \( l \) is the mean chord length of the volume, \( y = \frac{\varepsilon_s}{l} \)

Unit for \( L \) and \( y \) is \( \text{J m}^{-1} \), a frequently used unit is \( \text{keV} \mu\text{m}^{-1} \)
LET doesn’t take into account the random nature of energy loss along the track.

Lineal Energy is a stochastic quantity. The energy imparted by single events forms a distribution.
You can measure a distribution of dose in lineal energy with a TEPC

(But ICRP isn’t crazy about lineal energy)
ICRP defines the Quality Factor in terms of LET
Dose Equivalent Quantities

- **Dose equivalent**, $H$, at a point in tissue is given by
  
  $$H = Q D,$$

  where $Q$ is the quality factor and $D$ is the absorbed dose at that point.

- **Quality factor**, $Q$, weights absorbed dose at a point for biological effectiveness of charged particles producing the absorbed dose
  
  $$Q = 1/D \int Q (L) D_L \, dL$$

  Unit is J kg\(^{-1}\) with the special name sievert (Sv)
ICRP defined the protection quantities for limitation. They are based on mean values defined in the body and are not measurable.

ICRU defined the operational quantities for practical measurements and they are referenced to a point in a phantom or the body.
ICRP Protection Quantities

- **Equivalent dose**, \( H_T = \sum w_R D_{T,R} \), where \( D_{T,R} \) is the mean absorbed dose in tissue or organ, \( T \), due to radiation \( R \) and \( w_R \) is the radiation weighting factor.

  Note: \( w_R \) is defined for the incoming radiation.

- **Effective dose**, \( E = \sum w_T H_T \) where \( H_T \) is the equivalent dose in the tissue or organ, \( T \), and \( w_T \) is the corresponding tissue weighting factor.

Unit for both is J kg\(^{-1}\) with the special name sievert (Sv)
Fig. 1. The radiation weighting factor $w_R$ for neutrons introduced in *Publication 60* (ICRP, 1991) as a discontinuous function of the neutron energy (- - -) and the proposed modification (—).
ICRU Operational Quantities

- **Ambient dose equivalent**, $H^*(d)$, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth of $d$ mm on the radius opposing the direction of the aligned field.

- **Personal dose equivalent**, $Hp(d)$, is the dose equivalent in soft tissue, at a depth of $d$ mm, below a specified point on the body.

Unit for both is $\text{J kg}^{-1}$ with the special name sievert (Sv).
The composition of the ICRU Sphere is: 76.2% O, 11.1% C, 10.1% H and 2.6% N, with a density of 1.00 g cm\(^{-3}\)

But, no practical substance has the composition of ICRU tissue and unit density – and ICRU 39 recommended the ICRU-Sphere as a “suitable” phantom for personal dosimeter calibrations—fortunately they came to their senses in ICRU 43

Thoughts about International Committees –
Words of Wisdom

“No one should be allowed to serve on an ICRU or ICRP committee unless they have held a CP or Snoopy in their hand (and made measurements) in the five years prior to their appointment.”

(Bob Schwartz – NIST, Emeritus)
The fluence-to-dose equivalent conversion coefficient, $b_\Phi$, is the quotient of the dose equivalent, $H$, and the fluence, $\Phi$, at a point in the radiation field, undisturbed by the irradiated object,

$$b_\Phi = \frac{H}{\Phi}$$

A fluence-to-dose equivalent conversion coefficient requires a statement of the type of dose equivalent, i.e. ambient dose equivalent, personal dose equivalent
Measuring or Calculating Dose Equivalent

- If we were to measure (or calculate) a basic radiometric quantity such as fluence we could use
  \[ H = \int b_\Phi(E) \Phi_E(E) \, dE \]

- Or, if we had an instrument that had a perfect response with the same shape as the fluence-to-dose equivalent conversion coefficient vs. energy we could just record its reading.

- But, there are no perfect instruments or dosimeters.
Accelerator Radiation Fields

- The design and operating conditions at an accelerator present challenges to personal dosimetry.
- For example, new experiments may mean changes in shielding locations and beam lines.
- Accelerators are generally large and may have many access points – different fields at different places.
PSI - 590 MeV Main Cyclotron with lots of beam lines and target stations
BEVALAC in “Ye Olden Dayes”
Radiations Present

- What types of radiations might be present in accelerator workplaces? Answer: All types
- Primary beam energies can be extremely high
- Interactions with any nearby matter produce lots of secondary radiation
- Work in another area of radiation protection has benefited accelerator radiation protection
Aircrew and Astronaut Dosimetry

Mitaroff and Silari, RPD 102, 7-22 (2002)
At CERN - Spectroscopic and dosimetric measurements have been made on top of the iron and concrete shields

Mitaroff and Silari, RPD 102, 7-22 (2002)
Mitaroff and Silari, RPD 102, 7-22 (2002)
Aircraft and CERF
Similarity of Neutron Spectra

Mitaroff and Silari, RPD 102, 7-22 (2002)
Fortunately for us, most workplaces are on the other side of thick shielding

- Predominant radiations in workplaces include photons, neutrons, possibility muons
- Personal dosimeters are capable of detecting and measuring dose equivalent delivered by photons and other low-LET radiations
- Personal dosimeters are also capable of detecting and measuring dose equivalent delivered by neutrons
- Combination dosimeters may be used for both
Time for a Break?
Radiation Detectors for Personal Dosimetry

- Detectors make use of materials with large absorption cross sections for photons and neutrons.
- It’s helpful if those materials are similar in composition to tissue.
- Photon detectors use LiF, Al$_2$O$_3$, Li$_2$B$_4$O$_7$, CaSO$_4$, etc.
- Neutron detectors use $^6$LiF, $^6$Li$_2$B$_4$O$_7$, $^3$He, BF$_3$.
Low-LET Personal Dosimeters

- **Dosimeter types include:**
  - Photographic Film
  - TLD/OSL
  - EPDs/Self-Reading

- **Dosimeter fluence response as a function of energy** is “relatively” flat

- **Corrections are “relatively” small**

- $Q$ and $w_R$ are 1

- Several calibration sources are equally good
How Similar are Detectors to Tissue?

- LiF:Mg,Ti is used in personal dosimeters, Mg and Ti present in trace amounts.
- LiF $Z_{\text{eff}}$ is 8.1 and $Z_{\text{eff}}$ of tissue is 7.4, nice, but energy response is a little more complex.
- Measured energy response is quite good over wide range.
LiF Energy Response

Measurements performed by a number of national labs

Hranitzky, Stadtmann and Olko
RPD 119, 483-486 (2006)
Figure 3. Photon energy–response of TL $\text{Al}_2\text{O}_3$:C detectors: evaluated (full line), calculated (dotted line) and measured (circles) values of relative TL efficiency.

Olko, Bilski, E.-Faramawy, Göksu, Kim and Kopec

Example of Combination Personal Dosimeter
(Photons, Neutrons, Betas)
A Couple of Other Designs
EPD and Self-Reading
Neutron Personal Dosimeters

- **Dosimeter types include:**
  - Photographic Film
  - TLD/Etched-Track
  - EPD/S/Self-Reading
  - Bubble

- **Dosimeter fluence response as a function of neutron energy is anything-but flat**

- **Corrections are relatively large**

- $Q$ and $w_R$ are $>1$

- **Calibration sources are problematic**
How Similar are Detectors to Tissue?

- Not very
- Detector materials with large neutron absorption cross sections have atomic compositions very different from tissue
- Perfect detector would have response like fluence-to-dose equivalent conversion coefficient
- Fluence responses of detectors aren’t very similar to the fluence-to-dose equivalent conversion coefficients as function of energy
Conversion Coefficients and Dosimeter Response

McDonald, Thomas and Schwartz, RPD, 78, 147 (1998)

Useful Materials for Neutron Dosimeters
(Not very tissue-like)
Some Types of Detectors/Dosimeters

**Personal**
- **Active**
  - EPDs
  - DIS
- **Passive**
  - TLD-Albedo
  - Etched Track
  - Bubble

**Area Monitors**
- **Active**
  - Moderator-based
  - $^3$He or Scintillator
- **Passive**
  - Moderator + TLD or Foil
Examples of Dosimeter Response

Relative personal dose equivalent response as a function of neutron energy for a TLD-albedo dosimeter

Relative personal dose equivalent response as a function of neutron energy for two etched-track dosimeter types with boron-loaded Teflon converter covers

ICRU 66, Neutron Dosimetry
EPD Personal Dose Equivalent Response

\[ H_{\text{pm}}(10) / H_{\text{pc}}(10) \]

\[ E_n / \text{MeV} \]

Potential Problems/Challenges

- TLDs and OSL **photon** dosimeters have some response to neutrons – this must be taken into account.
- The responses of these detectors at high photon energies (>20 MeV) is unknown.
- At high doses, response may (will) be non-linear.
- EPDs may be sensitive to beam’s time structure.
- EPDs may also be sensitive to EM/RF.
- EPDs are expensive – but have some advantages.
Advantages – Passive Dosimeters

- TLD and OSL personal dosimeters for low-LET radiation are compact, inexpensive, reusable, stable and reasonably reproducible
- The dosimeters and readers are commercially available
- Readings can be traceable to national standards for some radiations
- They can pass DOELAP/NVLAP proficiency tests
Advantages – Active Dosimeters

- EPDs provide an instant readout
- They can indicate accumulated dose equivalent and dose equivalent rate
- They provide an alarm or multiple alarms
- Their readings can also be traceable to national standards
- Some models have also passed DOELAP/NVLAP proficiency tests
Personal Dosimetry Measurements

- In the workplace most personal dosimeters measure zero dose (or less sometimes)
- The “accuracy” of personal dosimetry is a difficult number to estimate
- DOELAP/NVLAP proficiency tests demonstrate that most are within 15-20% of conventionally true value – In the lab
- How accurate is a particular worker’s dose?
- Anybody want to guess?
Contributors to Uncertainty in Worker’s Dose

- Improper wearing of dosimeter (or not wearing at all)
- Albedo dosimeter swinging away from body on lanyard
- Environmental conditions (Once my dog ate my dosimeter – True Story!)
- Signal build-up in TL detector. Not all of signal is annealed out
- Angle of incidence of radiation – and other things
We can control some things

- Readout procedure constancy or consistency
- Stability of readout equipment
- Environmental conditions in the Dosimetry Lab
- Computer based checks help
- In-House calibration (or check) sources
- Internal Audits are a must
- Refer to ICRU 76, “MQA for Ionizing Radiation Dosimetry”
Some Important Items in Dosimeter Processing

- Personnel
- Accommodation and environmental conditions
- Test and calibration methods
- Equipment
- Measurement traceability
- Handling and transportation of test and calibration items
- Assuring the quality of test and calibration results
- Complete reporting of the results
A Word about Handling and Transportation of Dosimeters
Can we do away with measurements altogether and save ourselves a lot of headaches?

What do you think?

I’m an experimentalist – You know what I would say

But…
Computational Dosimetry — Siebert and Thomas, RPD 70,371 (1997)

Physical Quantities
- Fluence, Kerma, Absorbed Dose

Measurements and Conversion Coefficients

Operational Quantities
- Ambient Dose Equivalent
- Personal Dose Equivalent

Calibration

Instrument Response

Calculations and Conversion Coefficients

Protection Quantities
- Equivalent Dose
- Effective Dose

Conservative Approximation
Some Popular Programs

I don’t know anything about these programs, but I do have funny story about backscatter calculations – Anyway I think it’s funny

- MCNPX
- Fluka
- EGS-4
- How do you know they give the correct results?
EURADIOS Intercomparison

Normalized response data for Element 1, the $^6$LiF chip exposed to direct neutrons and shielded from albedo.

Tanner, et al., RPD 110, 769 (2004)
There are also newer anthropomorphic phantoms

I don’t know anything about these either

- MIRD
- Voxel VIPMAN
- Hybrid NURBS
- DICOM
- Golem

Folks can calculate Effective Dose if they know the distribution of fluence in energy and angle
Calibration and Traceability

- **Calibration** is a set of operations that establish, under specified conditions, the relationship between values indicated by a dosimeter, and the corresponding known (i.e., conventionally true) values of the quantity to be measured.

- **Traceability** is a property of a measurement result relating the result to a stated metrological reference through an unbroken chain of calibrations.
Calibration of Personal Dosimeters

- Calibration determines the relationship between the indication of device and the conventionally true value (CTV) of a quantity.

- A calibration coefficient, $N$, multiplied with the indication or reading, $M$, yields the CTV [$N \cdot M = CTV$].

- Calibration is carried out under standard test conditions – Facility dependent effects are corrected.

- The calibration quantity should be stated, i.e. dose equivalent calibration, fluence calibration.

- Reported results of calibration measurement are incomplete without a statement of the uncertainty.
Potential Problems/Challenges during Calibration

Differences between workplace and Cal Lab

Clean, neat, low scatter

Not so much
Calibration Conditions for Personal Dosimeters

- Most dosimeters are calibrated on a phantom representing the trunk or extremities.
- Many dosimeters need backscatter from phantoms (TLD-albedo).
- Some, like etched track, don’t care if there’s a phantom.
- For constancy checks, a simplified geometry (no phantom) could be used.
At the PNNL Cal Lab, the circular table is used for constancy checks.

A large number of dosimeters can be set in a circle at 1 m from a $^{137}\text{Cs}$ source or $^{252}\text{Cf}$ source.

But, if you have to use a phantom...
ISO-Recommended Phantoms

- Water-filled PMMA Tank (30x30x15-cm)
- Water-filled PMMA Cylinder (7.3 cm d. x 30-cm)
- PMMA Rod (1.9 cm d. x 30-cm)
Practical Calibration Geometry for Personal Dosimeters

Phantom

Dosimeter Reference Point is Placed at Point of Test

Radiation

Dosimeter

Phantom
US Calibration Phantoms

- DOELAP and NVLAP use 30×30×15 cm PMMA phantoms for whole-body dosimeters.
- The dosimeter is fixed on the front face of the phantom (reference direction normal to face) and reference point at point of test.
- The central portion of the phantom is irradiated relatively uniformly so up to five dosimeters at a time can be placed on the face of the phantom.
Fluence spectrum difference between workplace and Cal Lab

- For a dosimeter that has a response dependent upon energy, calibration using a source with a fluence spectrum different from that in workplace give an incorrect calibration

- So, you can…
  - Apply corrections for each workplace
  - Use the workplace spectrum as calibration source
  - Establish simulated workplace source(s) in Cal Lab
Calibration Source Spectrum and Workplace Spectrum

$^{252}$Cf spectrum is used in DOELAP proficiency tests

Neutron energy spectrum outside of beam enclosure at Fermilab
[J.D. Cossairt, TM-1834, Rev. 9B (2007)]
Maybe Use Spectrum Similar to Workplace Field

Results were re-normalized to a single CERF-specific calibration coefficient

Stewart, McDonald, Otto and Loesch. RPD, 87, 77-86, 2000
Some Important Items in Calibration

- Personnel
- Accommodation and environmental conditions
- Test and calibration methods
- Equipment
- Measurement traceability
- Handling and transportation of test and calibration items
- Assuring the quality of test and calibration results
- Complete reporting of the results
- What is always part of the reported result?
Quality Assurance and Documentation

- Why establish a quality assurance program? Usually, because you have to
- A quality management program will help you to become accredited by DOELAP or NVLAP
- The results of radiation protection measurements help to protect workers
- Our work is under more scrutiny than ever
- You need procedures to catch and correct errors before they leave your lab, and before the auditors find them
Quality System and Quality Manual

- ICRU Report 76 “Measurement Quality Assurance for Ionizing Radiation Dosimetry”
- ISO 17025 “General Requirements for the Competence of Calibration and Testing Laboratories” –

Sample of contents:

- Laboratory policies and procedures
- Laboratory organization
- Quality performance goals
- Competence and training of staff
- Records management
- Equipment specifications
- Reviews and audits
Document Everything

- “If it is not documented...it doesn’t exist”

- Documentation is the best insurance when something goes wrong or when somebody quits

- It’s nice to have everything stored in a computer, but...computers are sometimes invaded by gremlins

- When a piece of equipment dies, and it will die at the most inconvenient time, having all the original paperwork will be very useful for writing a new purchase requisition
Conclusions

- High quality personal dosimetry can be (and is being) performed at accelerator facilities
- Past performance in DOELAP has demonstrated this
- But, lately there have been some findings and problems
- The performance tests are worthwhile, but quality assurance has to be maintained every day
- Understand and believe that you will make mistakes – what counts is how you fix them – Have a plan
Concluding Conclusions

- Assigned Reading
  - ISO Standard 17025
  - ICRU Report 76
  - ICRU Report 66
  - ANSI N13.11
  - 2007 ICRP Recommendations
  - Dosimetry for Radiation Processing, McLaughlin et al. (Taylor and Francis, 1989)

- Have a look at Heinrich et al., RPD 86, 253 (1999) – An excellent primer on Cosmic Ray Physics
That’s All Folks

Tanks fer lendin’ me yer ears