Nuclear Medicine Shielding and Dosimetry

Bushberg Chapters 23 and 24
& Other Loose Ends…

Adam Alessio, Ph.D.
aalessio@u.washington.edu
Division of Nuclear Medicine
Dept of Radiology

Lectures at: http://depts.washington.edu/uwmip/

Once again, a meeting between management and the Plutonium Truckers' Union grows tense.

Review from Last Week:
Intro to Emission Tomography - From R. Miyaoka

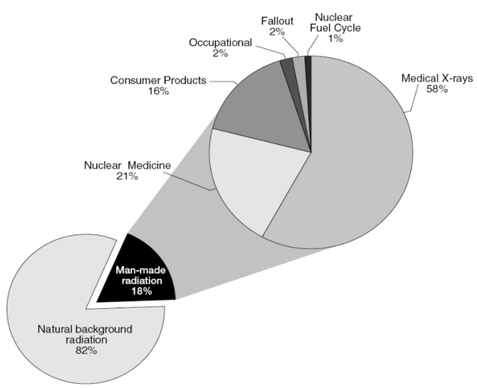
SPECT - Single Photon Emission Computed Tomography
- Detector orbits - 180, 360 degree, auto-contour

PET - Positron Emission Tomography
- Detection of two photons in coincidence - electronic collimation
- Types of events - trues, randoms, scatter
- Modes of acquisition - 2D and 3D

Data corrections for quantitative imaging
- Attenuation - easier in PET than SPECT; both moving toward using CT for attenuation map
- Scatter - PET (model based); SPECT (energy based)
- Randoms - PET only
- Normalization - SPECT requires longer normalization than planar gamma camera

Image reconstruction
- Filtered Back Projection versus Backprojection
- OSEM - iterative image reconstruction

Sources of Radiation Exposure in U.S.



This figure is based on data from "Ionizing Radiation Exposure of the Population of the United States", *National Council on Radiation Protection and Measurements*, No.93, 1987.

Dosimetry Descriptors - From Ionizing Radiation

Exposure:
Charge per mass, **Coulomb/kg = 3876 roentgens**
Can be measured directly
Does not account for biological effects

Absorbed Dose:
Energy per mass, Joules/kg = **gray (Gy)** = 100 rads
Usually calculated from exposure measurement
Does not account for biological effects

Equivalent Dose:
(Absorbed Dose) * radiation weighting factor (w_R or Q factor)
Also energy/mass, but units are **sieverts (Sv)** = 100 rem
Biological effects of absorbed dose depend on the type of radiation

Effective Dose:
Sum Over All Tissues[(Equivalent Dose$_T$) * tissue weighting factor (w_T)]
Also measured in **Sv**

The risk of cancer from a dose equivalent depends on the organ receiving the dose. The quantity "effective dose" is used to compare the risks when different organs are irradiated.

Estimating Effective Dose

To go from absorbed dose (Gy) to equivalent dose (Sv), need:

Radiation weighting factors

Type	w_R
Photons	1
Electrons (β), muons	1
Neutrons (varies with energy)	5-20
Protons	5
alpha (α), heavy nuclei	20

For CT and PET, 1Gy = 1Sv

International Commission on Radiological Protection, ICRP, Publ. 60, 1990 (www.icrp.org, *Annals of the ICRP*)

To go from Equivalent Dose (Sv) to Effective Dose (Sv), need:

Tissue weighting factors

Tissue or organ	w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

$$w_T = \frac{D_{all}(P)}{D_T(P)}$$

$D_{WB}(P)$ = absorbed dose to the *whole body* that has probability *P* of causing cancer

$D_T(P)$ = absorbed dose in a *single organ, T,* that has probability *P* of causing cancer in that organ

Average Dose Equivalent

TABLE 23-3. AVERAGE ANNUAL OCCUPATIONAL EFFECTIVE DOSE EQUIVALENT IN THE UNITED STATES

	Average annual total effective dose equivalent	
Occupational category	mSv	mrem
Uranium miners[a]	12.0	1,200
Nuclear power operations[b]	6.0	600
Airline crews	1.7	170
Diagnostic radiology and nuclear medicine techs	1.0	100
Radiologists	0.7	70

Adapted for measurably exposed personnel from National Council on Radiation Protection and Measurements. *Exposure of the U.S. population from occupational radiation.* NCRP report no. 101. Bethesda, MD: National Council on Radiation Protection and Measurements, 1989.
[a]Includes 10 mSv (1 rem) from high LET (α) radiation.
[b]Includes 0.5 mSv (50 mrem) from high LET (α) radiation.
LET, linear energy transfer.

Bushberg et al, The Essential Physics of Medical Imaging, Lippencott, Williams & Wilkins, Philadephia, 2002.

ALARA: As Low As Reasonable Achievable

TABLE 23-18. NUCLEAR REGULATORY COMMISSION (NRC) REGULATORY REQUIREMENTS: MAXIMUM PERMISSIBLE DOSE EQUIVALENT LIMITS[a]

	Maximum permissible annual dose limits	
Limits	mSv	rem
Occupational limits		
Total effective dose equivalent	50	5
Total dose equivalent to any individual organ (except lens of eye)	500	50
Dose equivalent to the lens of the eye	150	15
Dose equivalent to the skin or any extremity	500	50
Minor (<18 years old)	10% of adult limits	10% of adult limits
Dose to an embryo/fetus[b]	5 in 9 months	0.5 in 9 months
Nonoccupational (public limits)		
Individual members of the public	1.0/yr	0.1/yr
Unrestricted area	0.02 in any 1 hr[c]	0.002 in any 1 hr[c]

[a]These limits are exclusive of natural background and any dose the individual has received for medical purposes; inclusive of internal committed dose equivalent and external effective dose equivalent (i.e., total effective dose equivalent).
[b]Applies only to conceptus of a worker who declares her pregnancy. If the limit exceeds 4.5 mSv (450 mrem) at declaration, conceptus dose for remainder of gestation is not to exceed 0.5 mSv (50 mrem).
[c]This means the dose to an area (irrespective of occupancy) shall not exceed 0.02 mSv (2 mrem) in any 1 hour. This is not a restriction of instantaneous dose rate to 0.02 mSv/hr (2 mrem/hr).

Radiation Safety

4 Principals to minimize exposure

1. Time
   - For NM, Decay considerations
2. Distance (inverse square law)
   - If exposure rate at 1 cm from a source is 100 mR/hr, what is the exposure rate at 5 cm?
3. Shielding…
4. Containment…

NM Shielding

- Specific Exposure Rate Constant (Γ)
  - Exposure rate in R/hr at 1 cm from 1mCi of specific radionuclide
  - Used to calculate exposure rate at any distance from particular radionuclide

$$\text{Exposure Rate (R/hr)} = \Gamma A / d^2$$ ★

Γ in $(R \cdot cm^2 / mCi \cdot hr)$
A = activity in mCi
d = distance in cm from source of activity

- Types of Shielding: Tungsten, Lead, or leaded glass.
- Examples: Syringes, Vials, Pigs (for transporting vials)

NM Shielding

Exposure rate constants for photons greater than 20 keV and 30 keV.

TABLE 23-14. EXPOSURE RATE CONSTANTS (Γ_{20} AND Γ_{30})[a] AND HALF VALUE LAYERS (HVL) OF LEAD FOR RADIONUCLIDES OF INTEREST TO NUCLEAR MEDICINE

Radionuclide	Γ_{20} ($R \cdot cm^2/mCi \cdot hr$)[b]	Γ_{30} ($R \cdot cm^2/mCi \cdot hr$)[b]	Half value layer in Pb (cm)[c,d]
Co-57	0.56	0.56	0.02
Co-60	12.87	12.87	1.2
Cr-51	0.18	0.18	0.17
Cs-137/Ba-137m	3.25	3.25	0.55
C-11, N-13, O-15	5.85	5.85	0.39
F-18	5.66	5.66	0.39
Ga-67	0.75	0.75	0.1
I-123	1.63	0.86	0.04
I-125	1.47	0.26	0.002
I-131	2.18	2.15	0.3
In-111	3.20	2.0	0.1
Ir-192	4.61	4.61	0.60
Mo-99/Tc-99m[e]	1.47	1.43	0.7
Tc-99m	0.62	0.60	0.03
Tl-201	0.45	0.45	0.02
Xe-133	0.53	0.53	0.02

[a] Γ_{20} and Γ_{30} calculated from the absorption coefficients of Hubbell and Seltzer (1995) and the decay data table of Kocher (1981):
Hubbell JH, Seltzer SM. Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest. NISTIR 5632, National Institute of Standards and Technology, May 1995.
Kocher DC. Radioactive decay data tables. DOE/TIC-11026, Technical Information Center, U.S. Department of Energy, 1981.
[b] Multiply by 27.03 to obtain $\mu Gy \cdot cm^2/GBq \cdot hr$ at 1 m.
[c] The first HVL will be significantly smaller than subsequent HVLs for those radionuclides with multiple photon emissions at significantly different energies (e.g., Ga-67) because the lower energy photons will be preferentially attenuated in the first HVL.
[d] Some values were adapted from Goodwin PN. Radiation safety for patients and personnel. In: Freeman and Johnson's clinical radionuclide imaging, 3rd ed. Philadelphia: WB Saunders, 1984:370. Other values were calculated by the authors.
[e] In equilibrium with Tc-99m.

Bushberg

NM Shielding

Raphex Question:

A radiation worker standing for 3 hours at 1 meter from a 5 mCi radioactive source, for which $\Gamma = 2.0$ R cm^2/mCi-hr, will be exposed to about _____ mR.

A. 0.6
B. 1
C. 3
D. 30
E. 300

Exposure = (Exposure Rate) x (time) = $[\Gamma \times A \times t]/d^2$.

NM Shielding: Lead Aprons?

- Lead aprons work fairly well for low-energy scattered x-rays (less than 60 keV) , but not for medium-energy photons

TABLE 23-15. EXPOSURE REDUCTION ACHIEVED BY A 0.5-mm LEAD EQUIVALENT APRON FOR VARIOUS RADIATION SOURCES

Source	Energy (keV)	Exposure reduction with 1 apron	No. of aprons to reduce exposure by 90% (i.e., 1 TVL)	Weight (lbs)
Scattered x-rays	10–30	>90%	~1	~15
Tc-99m	140	~70%	~2	~30
Cs-137	662	~6%	~36	~540

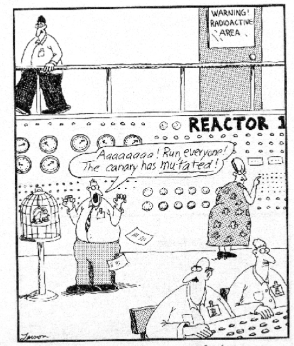
- Also, lead aprons not appropriate for Beta radiation. WHY?

High Z materials will facilitate bremsstrahlung x-ray production
Low Z materials are better shields for Beta's

NM Containment

- Contamination: uncontained radioactive material located where it is not wanted
- Controlled areas are locations where workers are under supervision of Radiation Safety Officers (RSO)
- Keep in mind:
  - Plastic-backed absorbent paper should be used on all work surfaces
  - If skin is contaminated, wash with soap and warm water
  - External contamination is bad, internal contamination is very bad
- Reduce Risk of Contamination:
  1. Label all radioactive materials
  2. Do not eat, drink, or smoke in radioactive work areas
  3. Do not pipette radioactive material by mouth
  4. Discard all radioactive materials and disposable work materials in Radioactive Waste receptacles
  5. Use caution with ventilation studies (Xe-133) (negative pressure with respect to hallway pressure)
  6. Report spills or accidents to radiation safety officer! (UW Radiation Safety : 543-0463. www.ehs.washington.edu/RadSaf/)

NM Containment



Inside a nuclear power plant

- Contamination control is monitored by
  - periodic Geiger-Mueller (GM) meter surveys (fairly easy to detect contamination unlike other hazardous substances)
  - Wipe tests are also performed: small pieces of filter paper (“swipes”) are placed in NaI gamma well counter
  - Areas that have twice the background radiation levels are considered contaminated
  - Each institution has guidelines for surveying
- Radioactive Material Spills
  - First Aid takes priority over personal decontamination over facility decontamination
  - Spill should be contained with absorbent material and area isolated and warning signs posted
  - Decontamination performed from perimeter of spill toward the center.

NM Containment

- Protection of Patient: Appropriate labeling, confirm patient identity
  - special care for pregnant or nursing women (unique guidelines)
    - Example: Use of I-131 greater than 30 microCi requires rule out of pregnancy with test
    - Example: After administration of just 5 microCi of I-131 requires 68 days of cessation of breast feeding
- Radionuclide Therapy
  - NRC regulations require that patients receiving radioimmunotherapy be hospitalized until the total effective dose to others will not exceed 5 mSv.
  - I-131 (used to treat thyroid cancer) has an 8 day half-life emitting high-energy beta’s and gamma rays (and Excreted in all bodily fluids)
  - Some Thoughts on Precautions for Home care following radioiodine therapy:
    - Majority of activity eliminated through urine (double-flush)
    - Wash all dishes and utensils immediately after use, sleep in separate bed, wash clothing separately from others
    - keep distance from others.

Summary of Dose Levels

Raphex Question:

Match the following exposure conditions with the appropriate dose.

A. 1 mSv
B. 0.1 mSv
C. 2 mSv
D. 2 μGy
E. 50 mSv

14. The maximum organ dose for patients undergoing nuclear medicine procedures
15. The regulatory weekly dose limit in controlled areas
16. The annual effective dose limit for a nuclear medicine technologist

14. E. 50 mSv = 5 rem
15. A. 1mSv = .5 rem
16. E. 50 mSv = 5 rem

Summary of Dose Levels

Regulations limit the radiation dose equivalent to patients undergoing radiological procedures to ____ mSv/year.

A. 500
B. 50
C. 5
D. 1
E. None of the above

Radioactive Waste Disposal

- **General Rule**: radioactive material is held for 10 half-lives and surveyed prior to discarding in regular trash
- **Liquid Waste**: At UW, we are allowed to dispose of material that is soluble into the sanitary sewer. A portion of the total UW allowance is allocated to each RAM (radioactive materials) lab where a sink is designated for liquid radioactive waste (about 200 microCi per quarter for common radiology isotopes)
- **Dry Waste**: At UW, Low activity material (those with long half-lifes) must be places in Low Specific Activity (LSA) boxes lined with plastic bags. Radiation safety staff disposes of this.
- Other guidelines for Infectious Wastes (some biological agent like blood), Mixed Wastes (radioactive and hazardous)

Raphex Question

12. The basic consideration in setting limits for disposal of radioactive materials into the sewer system is:

A. Contamination of the sewer.
B. Risk to swimmers.
C. Fish death.
D. Entrance into the food and fresh water chains.
E. Evaporation into the air.

D. Very low concentrations of radioactive materials, when ingested, can produce high, localized radiation doses to internal organs.

Raphex Question

Which of the following is true for low-level radioactive wastes, such as tubing and swabs contaminated with 99mTc?

A. They can never be thrown away since some activity always remains.

B. They can be thrown away immediately since the amount of activity is generally harmless.

C. They can only be disposed of by a commercial rad-waste service.

D. They can be stored until reaching background levels and then disposed of with other medical trash.

Regulatory Fun!

General Rule: “Cradle to Grave” for all radiation sources

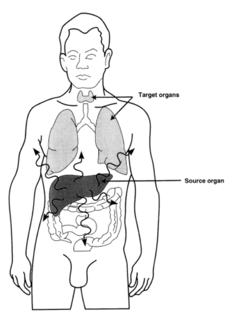
- **U.S. Nuclear Regulatory Commission (NRC)** regulates all material produced directly or indirectly from nuclear fission (many states have their own control programs with connections to the NRC)
  - Does not regulate cyclotron produced agents (F-18, Tl-201, I-123, etc.)
  - Regulate activities such as: Employee rights and responsibilities, survey requirements, warning signs, disposal procedures, storage, etc.…
- **FDA** regulates radiopharmaceutical development and manufacturing and often times installations (not directly involved in end user work except mammography)
  - Is involved in regulatory aspects of human research and education
- **U.S. Department of Transportation (DOT)** regulates transportation of materials
- Advisory Boards which suggest “Standards of Good Practice”: 1) Congress chartered “National Council on Radiation Protection and Measurements” (NCRP) and 2) “International Commission on Radiological Protection” (ICRP)

Radionuclide Therapy

- Thyroid cancer and hyperthyroidism often treated with NaI-131 (8-day half life)
- Patient allowed to leave hospital when activity in patient below 1.2 GBq (33mCi)
- We know exposure rate is proportional to administered activity…
- If we know the **Total Amount of Administered activity** and the **Initial Exposure rate**, we can measure exposure rate at any time and estimate the activity in the patient.
- Ex: Patient is injected with 4.4 GBq of I-131. At time of injection exposure rate at 1m is 40 mR/h. 2 days later, the exposure rate at 1m is 10mR/h. Can the patient go home?

NM Dosimetry

- **MIRD** (Medical Internal Radiation Dosimetry) Committee of the Society of Nuclear Medicine
  - Developed methodology for calculating radiation dose to selected organs and whole body from internally administered radionuclides
  - Two Elements:
    1) Estimation of quantity of radiopharmaceutical in various **SOURCE** organs
    2) Estimation of radiation absorbed in selected **TARGET** organs



Source Concerns? 1? 2?
Target Concerns? 1? 2?

MIRD Formalism

For a Source Organ (r_h)
and a target organ (r_k)
the Mean Dose (D_{r_k}) to a particular organ is

$$D_{r_k} = \sum_h \tilde{A}_h S(r_k \leftarrow r_h) \quad \bigstar$$

sum over all sources

where $\tilde{A}_h$ (μCi-hr) is the cumulated activity for each source organ and S (rad/μCi-hr) is a factor describing absorbed dose in target for each unit of activity in the source organ

MIRD

- Cumulated Activity in Source Organ:
  Total number of disintegrations from radionuclide located in particular source organ.
  - Depends on:
    1) Portion of injected dose taken up by source organ
    2) Rate of elimination from source organ
- Assume fraction (f) of injected activity is localized in source organ
- Assume exponential physical decay of radionuclide (Half Life: T_p)
- Assume exponential biological excretion from source organ (Half Life: T_b)

Total exponential Effective Half Life (T_e):

$$T_e = \frac{T_p \cdot T_b}{T_p + T_b} \quad ★$$

Activity remaining in organ at time t: $A_t = f A_0 \exp(-\frac{0.693}{T_e} t)$

MIRD

- Cumulated Activity in Source Organ (cont'd.)
  - Now that we have activity at time t, need cumulative activity (Sum activity over all time)

$$\tilde{A}_h = A_0 \cdot f \cdot 1.44 T_e \quad ★$$

$$(\mu\text{Ci} \cdot \text{hr})$$

- S Factor : Dose to target organ per unit of cumulated activity in a specific source organ
  - Specific to each source/target combination and radiation type
- Putting it back together:

$$D_k = \sum_h \tilde{A}_h S(r_k \leftarrow r_h)$$

MIRD simple example

- Patient is injected with 5mCi of Tc-99m-sulfur colloid. What is the absorbed dose to the a) liver and b) kidneys?
- Source Organ: Liver (assume all activity in liver, uptake in liver is instantaneous, and no biologic removal)
- Step 1: Find Accumulated Activity:

$$T_e = \frac{T_p \cdot T_b}{T_p + T_b} = T_p = 6.02\,\text{hr}$$

$$\tilde{A}_h = A_0 \cdot f \cdot 1.44 T_e =$$

$$5{,}000\,\mu\text{Ci} \times 1 \times 1.44 \times 6.02\,\text{hr} = 4.3 \times 10^4\,\mu\text{Ci} \cdot \text{hr}$$

- Step 2: Find S factors and organ doses

$$D_k = \sum_h \tilde{A}_h S(r_k \leftarrow r_h)$$

Lookup from Table:

[illegible]

[illegible]

$$D_{\text{liver}} = 2.0\ \text{rad}$$

$$D_{\text{kidneys}} = 1.7\ \text{rad}$$

Another MIRD example

- Dose calculation for a time-varying activity input: Intravenous injection of human albumin microspheres labeled with 10mCi Tc-99m are taken immediately in the lung and then released to other organs. What is the total absorbed dose in the liver? Kidneys?
- Same Steps as before, Need understanding of Accumulated dose in all source organs. Need to find total contribution of all source organs to target organs..

MIRD Discussion

Raphex:

In **I-131** therapy for thyroid cancer, the whole body clearance curve is commonly plotted versus time. The radiation absorbed dose to the patient is proportional to the _____.

A. Administered activity of I-131
B. Administered activity per unit body surface area
C. Administered activity per unit body weight
D. Peak counts in the clearance curve
E. Area under the clearance curve normalized to per unit body weight

E. The absorbed dose depends on the patient specific clearance kinetics. The same activity administered to two different patients of the same weight could result in different absorbed doses, if they metabolized and cleared the **I-131** at different rates.

MIRD Limitations

- MIRD provides reasonable estimates of organ doses (but could be off by as much as 50%)
- Limitations:
  1. Radioactivity assumed to be uniformly distributed in each source organ
  2. Organ sizes and geometries idealized into simple shapes to aid mathematics
  3. Each organ assumed to be homogenous in density and composition
  4. Reference phantoms for “adult”, “adolescent”, and “child” not matched to dimensions of specific individual
  5. Energy deposited is averaged over entire mass of organ when in reality effect occurs on molecular/cellular level
  6. Dose contributions from bremsstrahlung and other minor radiation sources ignored
  7. With few exceptions, low-energy photons and particulate radiation assumed to be absorbed locally (don’t penetrate)

Review with Raphex

Match the following units with the quantities below:

A) Bq
B) Sv
C) C kg^{-1}
D) Gy
E) J

5. Absorbed dose
6. Activity
7. Exposure
8. Dose equivalent

Some Discussion Questions

If a 5 year old girl (Suzy) is injected with 7mCi of F18 FDG and a 25 year old girl (Franny) is injected with 7mCi of F18 FDG for PET Exams…

1. Who received more activity?
2. Who received more absorbed dose?
3. Who received more equivalent dose?
4. Who received more effective dose?
5. Who has a greater radiation induced risk?

Some Discussion Questions

If a 5 year old girl (Suzy) stands 10 meters from a F-18 source and a 25 year old girl (Franny) stands 10 meters from a I-131 source…

1. Who received more absorbed dose?
2. Who received more effective dose?
3. Franny walks away and Suzy stands near source for 3x as long as Franny… Who received more effective dose?

Loose Ends…Counting Error

Distributions of interest:

1. Binomial- For binary process (success/failure), (photon detection/no-detection)
2. Poisson - Binomial process basically Poisson when success is rare and have a lot of tries (large N) -
   !! Nuclear Decay and Detection Behaves Like Poisson !!
3. Gaussian - Poisson process is basically Gaussian when N>20

When estimating uncertainty in single measurement, best we can do is assume measurement is the mean of the distribution…

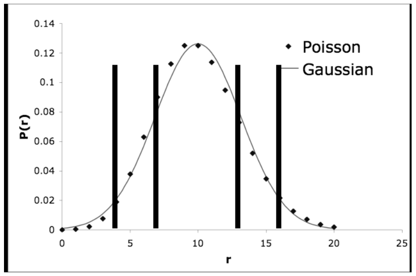
Key Item to remember:

For Poisson Distribution, the mean = variance

Certainty of Single Measurements

Detected 10 counts, how certain are we about that measurement?

- We know true number of counts is distributed as a Poisson (assume has a mean of 10…best we can do… (If mean =10, variance = 10, standard deviation = 3.2)
- Looks a lot like a Gaussian (mean=variance=10, See below)



$\mu \pm \sigma$ = 10 ± 3 ⇒ 68.3% of events

$\mu \pm 2\sigma$ = 10 ± 6 ⇒ 95.3% of events

How accurate is a single measurement?

- Take a single measurement of radioactive source and detect 100 events.
  - Estimate that the real number of detectable events is 100 (variance = mean with Poisson, so var =100, so sd =10.
    How close is this to the truth?
    68% Probability: 90 < truth < 110 est +- sd
    95% Probability: 80 < truth < 120 est+- 2sd
    99% Probability: 70 < truth < 130 est+-3sd
- Take a single measurement of radioactive source and detect 10,000 events.
  - Estimate that the real number of detectable events is 10,000.
  How close is this to the truth?
  68% Probability: 9900 < truth < 10,100
  95% Probability: 9800 < truth < 10,200
  99% Probability: 9700 < truth < 10,300

Adam Alessio, UW Radiology, aalessio@u.washington.edu

Raphex Question

A series of measurements has a mean of 100 counts. There is 68% confidence that the true measurement is in the range…

A. 95-105
B. 90-110
C. 68-137
D. 50-150
E. 33-167

Loose Ends…Statistics

Items of Particular Importance:

1. We use statistics to describe random phenomena
2. To describe central tendency of phenomena often use mean
3. To measure dispersion, often use variance (dispersion around mean) and standard deviation (square root of variance, has same units as mean!)
4. Error Propagation - When adding or substracting random numbers, the variance adds together (standard deviation adds in quadrature)

$$x_1 - x_2 = x_3$$
$$\mu_1 - \mu_2 = \mu_3$$

If you substract 2 random numbers, the mean is the subtraction of the 2 means.

$$\sigma_1^2 + \sigma_2^2 = \sigma_3^2$$

The variance of the new number is sum of two variances (new number is more noisy than first two numbers)

$$\sqrt{\sigma_1^2 + \sigma_2^2} = \sqrt{\sigma_3^2}$$

Identical to the standard deviations add in quadrature

Raphex Question

- If the background is 100 counts and the sample is 900 counts, the net standard deviation is:

A. 50.0
B. 28.3
C. 24.1
D. 40.0
E. 31.6

Raphex Question

- How many counts must be collected in an instrument with zero background to obtain an error limit of 1% with a confidence interval of 95%?

A. 1000
B. 3162
C. 10,000
D. 40,000
E. 100,000