Extreme Uncertainty: When Dose Reconstruction Becomes Doswaggery

Continuing Education Lecture 6
Health Physics Society 50th Annual Meeting
Spokane, Washington 13 July 2005

Daniel J. Strom
Pacific Northwest National Laboratory
strom@pnl.gov
+1 509 375 2626

Battelle

Pacific Northwest National Laboratory

The Problem

- Many people, including health physicists, often use the term "dosimetry" for any process that produces a number in "dose-like" units
  - roentgens, rads, rems, coulombs per kilogram, grays, or sieverts
- Not all such "doses" are created equal in terms of
  - their basis in measurements and/or observations
  - how well they represent deposition of ionizing radiation energy in living tissue
  - how well we know their value (uncertainty)
- So, rem is not a rem is not a rem…

Outline

- Why we [are forced to] do dose reconstruction
- What we should call the results of uncertain dose reconstructions
  - Dosimetry: Uncertainty is dominated by what we measure
  - Dosinference: Uncertainty is dominated by what we don't measure
    - consensus or expert inferential models
    - consensus or expert parameters of inferential models
  - Doswaggery: Uncertainty is dominated by what we make up (leaps of inference about what might have been)
- Examples of uncertain dose reconstructions
  - Radiographic examinations
  - Doses from inhalation intakes, including radon
  - Occupational exposure to neutrons
- Who are we kidding?

Purposes of Dose Reconstruction

- regulatory compliance
- epidemiologic research
- litigation
  - occupational exposures
  - environmental exposures including fallout
  - medical exposures
- [political forces have compelled us to engage in the] determination of probability of causation for cancers suspected of being caused by workplace exposure [subject to political rules]

Dosimetry
(*Measuring* Dose)

Dosimetry

- "dose" + metry
  - root is *metron* (Greek: to measure)
- current usage: any dose number is presumed to be the result of "dosimetry"
- thesis
  - If measurement or observation is the dominant activity, and
  - uncertainties in results are predominantly due to measurement uncertainty,

  use the word "dosimetry." Otherwise, maybe new terms would be more appropriate!

Measuring the Quantity of Radiation

- observation of biological response (e.g., erythema, chromosome aberrations)
- cloud chambers
- film blackening
- appearance or sound of bubbles in superheated liquids
- analysis of activation or fission product yield
- scintillations
- Čerenkov radiation (light)
- thermoluminescence (TL) or optically stimulated luminescence (OSL)
- observation of radiation damage (e.g., chemically etching damage in film, radiochromic changes, thermal and electrical conductivity changes, ESR in teeth and bones)
- chemical changes as quantitated by light absorption or nuclear magnetic resonance
- measurement of electric charge or current in solids (Ge and Si) or gases such as xenon, P10, or air, and
- calorimetry

Measuring Radioactive Material

- Measurements
  - radiometry (activity)
  - gravimetry (mass)
  - number of atoms (mass spectrometry)
  - chemical measures (moles)

Dosimetry for External Irradiation

- most measurements are *outside* of the human body
- want to know dose inside or at surface
- external irradiation: few inferential steps
  - absorption
  - albedo
  - spectrum changes
  - based on types, energies, directions of incident radiation
  - assumptions about person wearing dosimeter
  - neutrons still a challenge
- irradiation following intake or ontake of radioactive material
  - surgical implantation of dosimeters? no.
  - inference

Dosinference
(*Inferring* Dose)

Dosinference

- blend of "dose" + "inference" (Strom 2002)
- uncertainties associated with inferential steps dwarf uncertainties of measurement steps
  - exceptions: ^{3}H and alkali metals, e.g., ^{137}Cs
- measurements tend to be of dose-rate like quantities, rather than dose-like quantities
  - rate of photon emission from regions of body (in vivo counting)
  - count rate or numbers of atoms (TIMS, ICP-MS) in excreta
  - count rates from air samples
  - exception: chromosome aberrations
- infer activity (and its uncertainty) in organs and tissues from measurements and biokinetic models

Example: Committed Dose from Inhalation of Radionuclides

What's Uncertain When Inferring Intake?

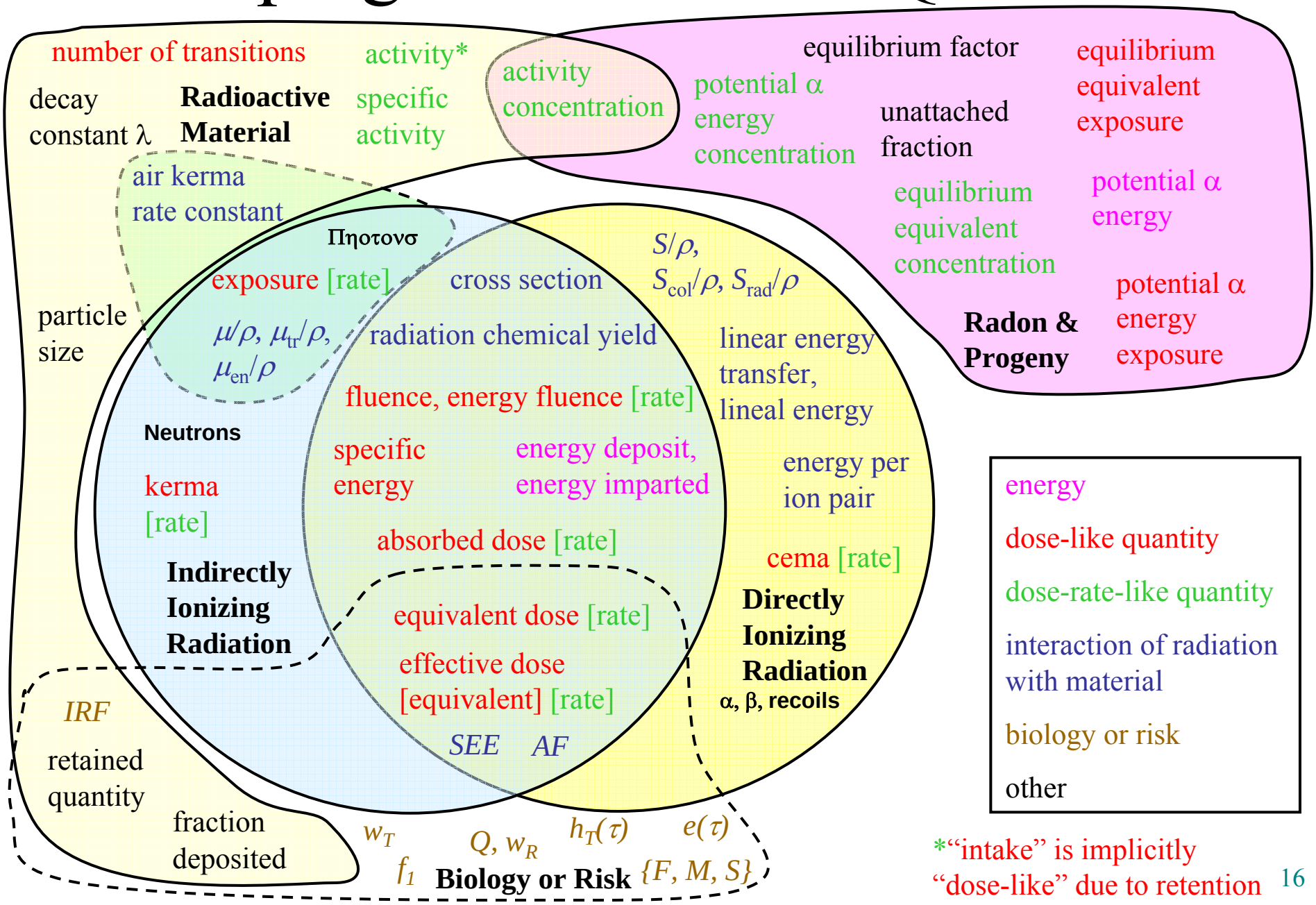
- Circumstances
  - time or time course of intake
  - route(s)
- Material characteristics
  - radionuclide mixture
  - particle size and shape
  - chemical form(s) and transportability (S, M, F, or real)
- Measurements
  - counting or measurement uncertainty
  - 24-h sample? simulated? adulterated or contaminated?
- Biological variability
  - availability and validity of model(s)
  - systematic differences between individual and models
  - among bioassay samples or measurements
- Interpretation
  - interference from environmental exposures
  - prior intakes

Catalog of Radiation Quantities Used in Dose Reconstruction that May Be Uncertain

Types of Radiation Quantities

- energy
- dose-like quantities (energy/mass)
- dose-rate-like quantities (power/mass)
- interaction of radiation with material (various)
- biology or risk (various)
- other

Groupings of Radiation Quantities



*"intake" is implicitly "dose-like" due to retention

Non-Measured or Rarely-Measured Parameters Used in Dosinference Following Inhalation

- particle size distribution
- respiratory tract clearance type: F, M, S or specific
- fractions deposited in various parts of the individual's respiratory tract
- individual's intake or retained quantity
- individual's number of transitions, *U*
- individual's intake retention fraction, *IRF*
- individual's uptake fraction from GI tract, f_1
- individual's absorbed fraction, *AF*
- individual's organ masses

Other Inputs to Dosinference that May or May Not Be Measured

- knowledge or guesses of time course and route(s) of intake
- identity of all radionuclides and proportions in a mixture
- chemical and physical form for ingestion, injection, wound, or dermal absorption from an ontake
- true daily excretion rate for in vitro bioassay (non 24-h samples)
- biokinetic models
  - Reference Man usually used, not individual data
  - individual chest wall thickness and ^{40}K corrections
  - site-specific solubility, e.g., Y-12's "Class Q" uranium

Air Sampling for Dosinference

- activity concentration, $\chi = A/V$ (Bq m^{-3})
- personal (breathing zone, BZ) air samplers
  - lapel
  - fixed head for glove box locations
- general area (GA) air samplers
- presumed to be representative of what worker inhaled
- may be way off for high-specific activity aerosols where one particle can be a significant fraction of an *ALI* (Birchall et al. 1991)
- For *average* inhalation exposures to high specific activity $^{238}PuO_2$ particles (10 g/cm^3, 5 μm AMAD, lognormal distribution GSD = 2.5) of 1, 2, 4, and 8 DAC-hours, ITRI's Monte Carlo analysis showed that most folks have zero intake, while some will exceed 2000 DAC hours (Scott et al. 1997)

Inhalation Exposure of Individuals

- The **exposure** Y (Bq h m^{-3}) over a period of time T (h) is

$$Y(T) = \int_0^T \chi(t)\,\mathrm{d}t$$

- Y is commonly normalized to the derived air concentration, *DAC*

$$Y_{\mathrm{norm},i}(T) = \int_0^T \frac{\chi_i(t)}{DAC_i}\,\mathrm{d}t$$

- *inhalation exposures* often given in *DAC*-h

Respiratory Protection

- Assigned Protection Factor, *APF*

$$APF = \frac{\chi_{\text{outside respirator}}}{\chi_{\text{inside respirator}}},$$

- *APF* is determined by regulator, e.g., 10 CFR 20 Appendix A
  - actual PF for workers may be *very* different!
- the **adjusted inhalation exposure** becomes

$$Y_{\text{norm, adjusted}, i}(T) = \frac{1}{APF}\int_0^T \frac{\chi_i(t)}{DAC_i}\,\mathrm{d}t$$

- *adjusted inhalation exposures* often given in *DAC*-h
- If stochastic *DAC*s are used, 1 *DAC*-h is a surrogate for 2.5 mrem of $H_{\mathrm{E},50}$, so *DAC*-hours from different radionuclides can be added

Additional Non-measured or Rarely-measured Parameters in Dosinference *from Air Monitoring*

- individual's breathing rate
- individual's nose or mouth breathing
- individual's respiratory protection factor, *PF*
- particle size distribution *inside the respirator*
- representativeness of the air sample: the one thing we are certain of is that the air that was sampled was ***not*** the air that was breathed!
- ***Note that there is no NVLAP or DOELAP program for accreditation, quality assurance, and quality control for air sampling measurements that are used to compute a 'dose of record.'***

Dosinference from Radon Progeny

- short-lived decay products of radon & thoron
  - radon concentration
  - equilibrium factor
  - stay time and diurnal variations
  - breathing rate (level of exertion)
  - nose breathing
  - smoking
  - unattached fraction
  - particle size (for attached fraction)

Dosinference from Radon Progeny

- ICRP (1995) “dose conversion convention”
  - 5 mSv/WLM rather than 12.5, based on epidemiology
- You’re lucky to get within a factor of 2

Example: Reconstructing Occupational Neutron Doses

Imputed Values

- to "impute" has taken the meaning to "make up a number"
  - Reissland (1982) used the term "notional dose" for what today is termed an "imputed dose"
- lost or damaged external dosimeter, spoiled bioassay or air sample
- imputation commonly done for regulatory compliance
  - interview worker & colleagues, dose rates, time-in-area
  - average preceding and subsequent dosimeter results
- can be very accurate
  - CARI-6 for air travel

  http://www.cami.jccbi.gov/AAM-600/610/600Radio.html
- can be done for "less than detectable" results

Uncertainty Components for Reconstructing Occupational Doses ($H_p(10)$) from Neutrons - 1

- Offsite dose not measured or records not transferred
- Offsite dose records transferred, unknown technology
- [Neutrons NOT monitored] AND [Individual potentially exposed]
- Dosimetry Technology Used (ISO Type B)
- Known/Unknown Calibration Source
- *Calibration Spectrum*
- Calibration Source Strength
- Calibration Room Scatter

Uncertainty Components for Reconstructing Occupational Doses ($H_p(10)$) from Neutrons - 2

- *Fading/Deterioration*
- QC on manufacturing, processing, and readout
- Units
- Conversion Factors
- *Worker Spectrum*
- Representativeness
- Uniformity of Irradiation
- Neutron Direction with respect to Worker

Uncertainty Components for Reconstructing Occupational Doses ($H_p(10)$) from Neutrons - 3

- Response to Interfering Radiations
- Similarity of Individual to Phantom
- Left Censoring
- Lost/Damaged Dosimeter(s)
- Dosimetry Technology Used (ISO Type A)
- Fraction of Time Dosimeters Worn
- Data Quality
- Imputation

Uncertainties

- Additive
  - Example: standard deviation *(SD)*
- Multiplicative
  - Example: geometric standard deviation *(GSD)*
  - National Academy of Sciences (NAS) 1989 methodology
  - Alternative methodology
- Need for both additive and multiplicative uncertainties

Uncertainty

- Not measurand variability, bias, precision, or error, but may be affected by these
- Additive
  - Example: standard deviation *(SD)*
- Multiplicative
  - Example: geometric standard deviation *(GSD)*
  - National Academy of Sciences (NAS) 1989 methodology
  - Alternative methodology
- Need for *both* additive and multiplicative uncertainties for neutron dose reconstruction

Additive Uncertainties

- Familiar to most people
- Normal distribution characterized by
  - a standard deviation *(SD)*
  - *mean = median = mode*
- Coefficient of variation, $CV = SD/mean$
- Interval nonnegative when CV is small, e.g., < 0.2
- When $CV > 0.2$, negative values and zero become increasingly probable
  - the *reciprocal* of a Normal distribution encompassing zero and negative values is intractable (it has no mean)

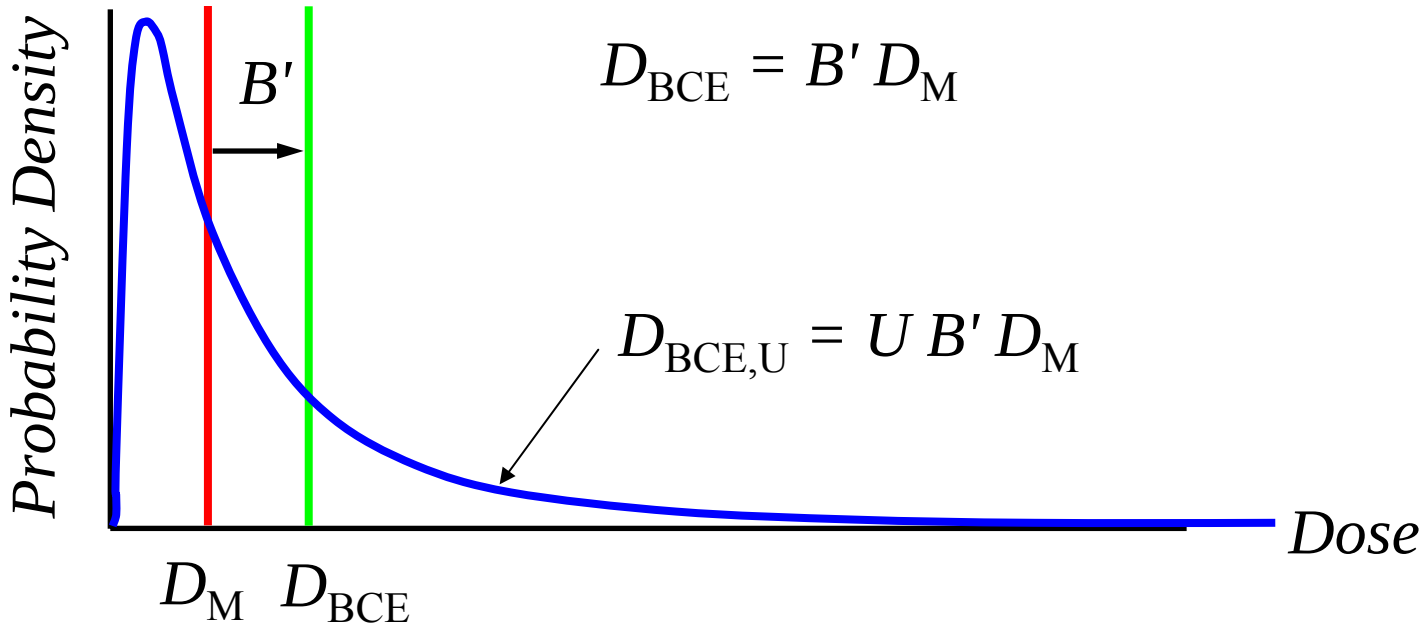
Multiplicative Uncertainties

- Not familiar to most people
- Lognormal distribution characterized by
  - a geometric standard deviation *(GSD)*
  - *mean* > *median* > *mode*
- Contrasting an *SD* with a *GSD*
  - *SD*: a "plus or minus" value
    - ~68% of values between *mean* – *SD* and *mean* + *SD*
    - ~95% of values between *mean* – 1.96 *SD* and *mean* + 1.96 *SD*
    - can include negative numbers
  - *GSD*: a "times or divided by" value
    - ~68% of values between *median* ÷ *GSD* and *median* × *GSD*
    - ~95% of values between *median* ÷ $GSD^{1.96}$ and *median* × $GSD^{1.96}$
    - 2-parameter lognormal cannot include negative numbers

For Each Uncertain Component,

- ISO Type A or B uncertainty?
- Effect on Individual's Dose
  - R = random or S = systematic
- If S, Is Bias Factor High or Low?
- Effect on Population's Dose
  - R = random or S = systematic
- If S, Is Bias Factor High or Low?
- Does uncertainty depend on dosimetry technology (Site, Time)?
- What action do we take?
  - Impute a dose or eliminate subject
  - None possible
  - Only in specific cases
  - Assign fixed *GSD* based on research
  - No information
  - Assign *GSD* based on extremes
  - Insufficient information
  - 2-fold variation: $GSD = 1.19 \sim 2^{(1/4)}$
- Assign a Confidence Code
- Compute
  - Independent Factors *GSD*
  - NTA *GSD*
  - TLND *GSD*

Create a Lognormal Uncertainty Distribution U



- D_{BCE} is the "bias-corrected estimate" of dose
- B' is the *multiplicative* bias-correction factor
- U is the lognormal uncertainty distribution whose mean = 1
- If the *mean* of U is 1, the *mean* of $D_{BCE,U}$ is *unchanged* by applying the uncertainty distribution

Result:
Asymmetric *K*-factors Around the *Mean* of *B′*

- *K*-factors are different above and below the *mean*

$$K_{1.96\ \text{Above Mean}} = GSD^{1.96} \exp(-\sigma^2 / 2)$$

$$K_{1.96\ \text{Below Mean}} = GSD^{1.96} \exp(+\sigma^2 / 2)$$

- The 2.5%^{ile} and 97.5%^{ile} values of *B′* are

$$B'_{2.5\%\text{ile}} = \frac{B'}{K_{1.96\ \text{Below Mean}}} \text{ and}$$

$$B'_{97.5\%\text{ile}} = B' \times K_{1.96\ \text{Above Mean}}$$

Overall $H_p(10)$ Geometric Standard Deviations

	Independent Factors *GSD*	NTA *GSD*	TLND *GSD*
GSD Component	2.39	2.80	1.28
Combined *GSD*		3.85	2.47
$K_{\text{Above Mean}}$		2.70	4.22
$K_{\text{Below Mean}}$		72.83	8.27

An Additive Factor Is Also Needed

- Problem: if D_M is zero, $D_{BCE,U}$ will be zero
  - NTA film often produced zeroes due to fading
  - even without fading, minimum detectable dose *MDD* ~ 0.5 mSv
- Solution: create a second uncertain probability distribution Δ_U that has a positive mean

$$D_{BCE,U,\Delta} = U \cdot \left(D_M + \Delta_U\right) \cdot B'$$

- Ideally, Δ_U would be the distribution of the measurand that leads to recorded results of zero
  - normal, triangular, rectangular, or lognormal distributions might be appropriate
  - a point estimate may also be used
  - mean might be chosen as ½ the minimum recorded dose
  - better methods, e.g., Strom (1986), Mitchell (1997)

Doswaggery:
(*Making Up* Dose)

Doswaggery

- blend of "dose" + "swag" (Strom 2002)
  - root is acronym for *scientific wild assumption guess* (US popular usage)
  - examples of *swags*
    - predicting the weather two weeks in advance
    - predicting the value of the stock market in a year
- uncertainties in assumptions dwarf even the uncertainties in the inferential steps, much less the uncertainties in the measurements
- may not rely on measurement at all, or may rely on measurements only tenuously associated with individual for whom a dose is being inferred

Doswaggery to Impute Doses

- not all imputed doses are doswags
  - production lines
  - radiology department with steady caseload
  - careful dose reconstructions such as RERF DS02
- examples of doswaggery:
  - assigning historical uranium miners potential alpha energy exposures (J h m^{-3} or WLM) based on measurements in similar mines
  - historical dose reconstruction for litigation in U mining, milling, refining in absence of any concurrent workplace measurements
  - some projections of future (50-year "committed") doses
  - population doses from high level waste repositories

Uncertainty Is Not *Necessarily* Error

- "The result of a measurement (after correction) can unknowably be very close to the value of the measurand (and hence have a negligible error) even though it may have a large uncertainty. Thus the uncertainty of the result of a measurement should not be confused with the remaining unknown error." – ISO (1995)
- a doswag *may* be accurate but *is* highly uncertain
- long-range weather forecasts are sometimes correct!

Word Choice Based on Uncertainty

Term	Typical Dominant Uncertainty				Ratio of 97.5%^{ile} to 2.5%^{ile} of Inferred Dose
	Measure-ments	Models	Model Parameters	Imputed Data	
Dosimetry	✓✓	✓	~	~	1.01 to 2
Dosinference	✓	✓✓	✓✓	~	2 to 20
Doswaggery	~	✓	✓	✓✓	>20

✓ denotes important; ✓✓ denotes very important; ~ relatively trivial

Calling a Spade a Spade…

- maybe it's time to choose different words when the dose in question is measured, inferred, or essentially assumed
- *dosimetry* when measurement uncertainty predominates
- *dosinference* when model parameter uncertainty predominates
- *doswaggery* when assumption or imputed value uncertainty predominates

Uncertainty, Variability, and Bias

- Uncertainty: you're not too sure of the value of the measurand
- Variability:
  - intra-subject variability: day-to-day differences
  - inter-subject variability: systematic differences between individuals (e.g., height)
- Bias:
  - value is systematically wrong
  - individual differs systematically from Reference Man
- Error: a mistake, a blunder
  - don't use the word "error" in place of uncertainty, variability, or bias

Measurements Used for Assessment of Doses from Intakes of Radioactive Material: Bioassay

- ***in vitro* assessment of internal radioactivity**
  - nasal swipes or smears: immediately after a suspected or verified accident
  - smears of skin or wash water
  - urinalysis
  - fecal analysis
  - analysis of other tissue material
  - analysis of swipe sample or air sample for particle size, solubility, and isotopic composition
- ***in vivo* assessment of internal radioactivity**
  - direct monitoring of skin
  - direct monitoring of wound
  - chest ("lung") counting
  - whole body counting

Two Ways to Determine Intake *I*

- use bioassay result and knowledge of time of intake
  - intake retention fraction (*IRF*)
    - for a given "bioassay compartment," e.g., urine, feces, lung retention
    - as a function of time since intake t_I (Potter 2002)

$$I(\mathrm{Bq}) = \frac{Activity\ in\ Bioassay\ Compartment}{IRF(t_I)}$$

- use air sample, stay time, breathing rate, and assigned protection factor

$$I(\mathrm{Bq}) = \frac{\chi(\mathrm{Bq\,m^{-3}})\,t(\mathrm{hours})\,(1.2\mathrm{m^3\,h^{-1}})}{APF}$$

From Intake to Effective Dose: *IRF* and *e*

- multiply *I* by effective dose per unit intake factor $e(\tau)$ (IAEA SS 115 or ICRP 68, 71, etc.)
- $e(\tau)$ depends on
  - route of intake
  - particle size (inhalation only)
  - chemical form
  - age
  - person (worker or public)

$$E(50) = I\, e(50)$$

Dosinference Example: Bioassay to Effective Dose

- routine 24-hour urine sample: 0.022 ± 0.005 dpm of $^{239+240}$Pu
- *DL* = 0.010 dpm
- Pu contamination near where he was working 200 days before
- Assume acute inhalation intake, 5µm AMAD Type S particles
- What *E*(50) would you assign to the worker?

Answer

- IRF_{urine}(200 d) = 1.61E-7 (Potter 2002 p. 772)
- *e*(50), 5µm = 8.3E-6 Sv/Bq (workers; IAEA SS 115 p. 153)
- Convert dpm to Bq (1 dpm = 1/60 Bq)
- 24-h urine excretion = (3.67 ± 0.83)E-4 Bq
- *(24-h Urine Bioassay Quantity)* ÷ *IRF* = 2280 ± 580 Bq
- $I \times e = E(50)$ = 0.0189 ± 0.0043 Sv = 18.9 ± 4.3 mSv
- uncertainty is doubtless ***much*** larger than the counting uncertainty

Potential Doswaggery Example: Radiation “Dose Reconstruction” from Medical X-Rays

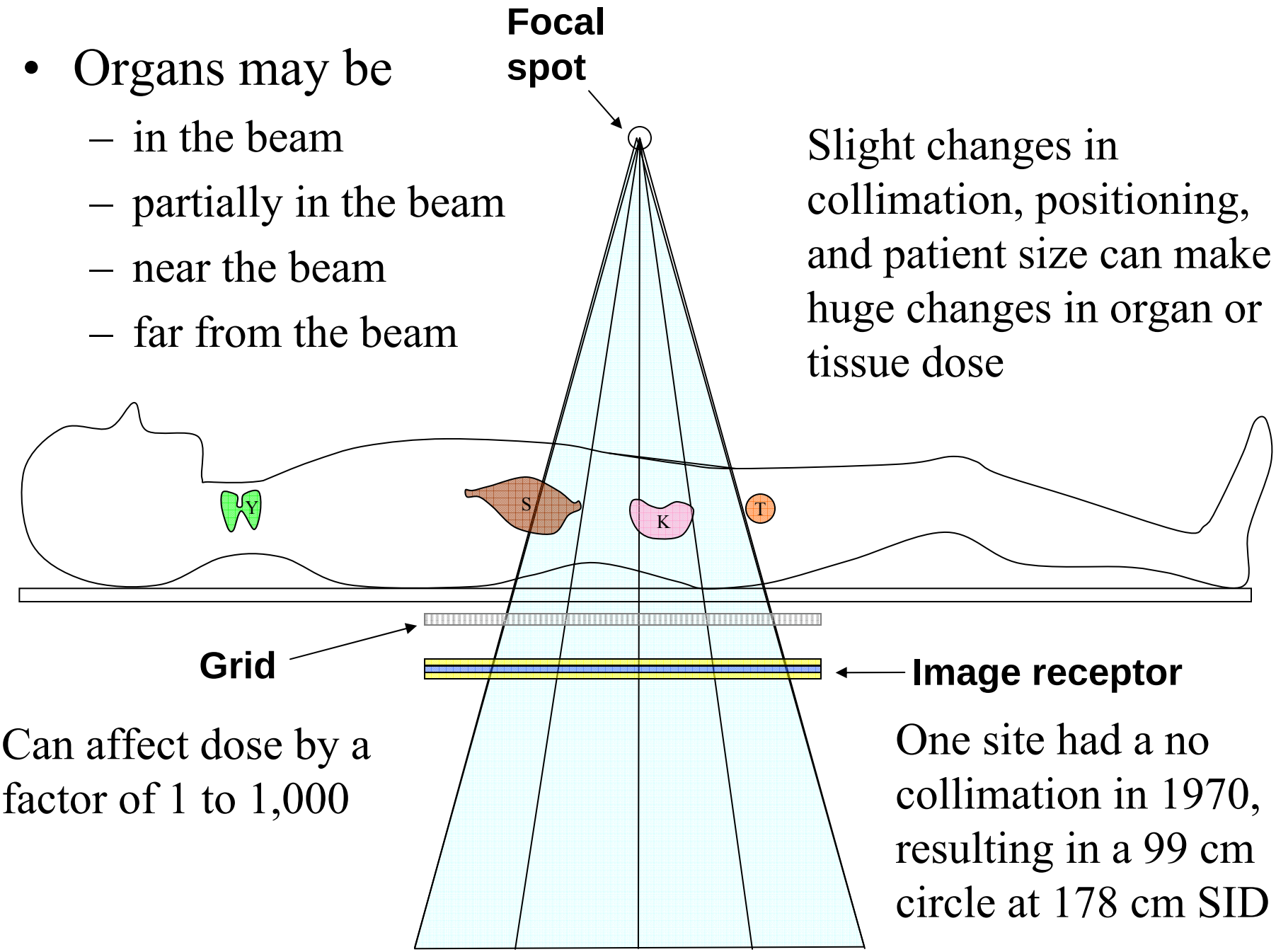
X-Ray Dose Reconstruction

- Reconstructing doses from past radiographic and fluoroscopic procedures may start from non-radiological assumptions and measurements
- Dependence of dose (that would have been causal to various cancers) on various parameters
- Degree of knowledge of those parameters
  - what's known and what's assumed
  - uncertainty in assumptions made in absence of evidence
- Postulated nature of uncertainty parameters
  - ISO GEUM Type A or Type B?
  - Random or systematic for an individual
- The Future: Monte Carlo uncertainty propagation

Organ or Tissue Dose due to Diagnostic X-ray Procedures Depends on

- Characteristics of the X-ray machine
  - Inherent & added filtration -- Uncertainty Range: ×4 at 100 kVp, ×10 at 45 kVp
  - Waveform (type of rectification): ×1.7
  - Type of target (e.g., tungsten): (74/42) = 1.76 (usu. ×1)
  - Condition of the target: ×1.5
- "Technic"
  - Source-to-image distance (SID), source-to-skin distance (SSD): ×2
  - Accelerating potential (kilovolts peak): $\propto(\text{kVp})^{2.0\text{-}2.5}$; ×2
  - Charge used in each exposure, expressed as the product of exposure time(s) and tube current (mA), in mAs (or mC): $\propto(\text{mAs})^{1}$; see below
- Projection, e.g., anterior-posterior (AP) lumbar spine
- Degree to which the beam was collimated: ×1,000

- Organs may be
  - in the beam
  - partially in the beam
  - near the beam
  - far from the beam



Slight changes in collimation, positioning, and patient size can make huge changes in organ or tissue dose

Can affect dose by a factor of 1 to 1,000

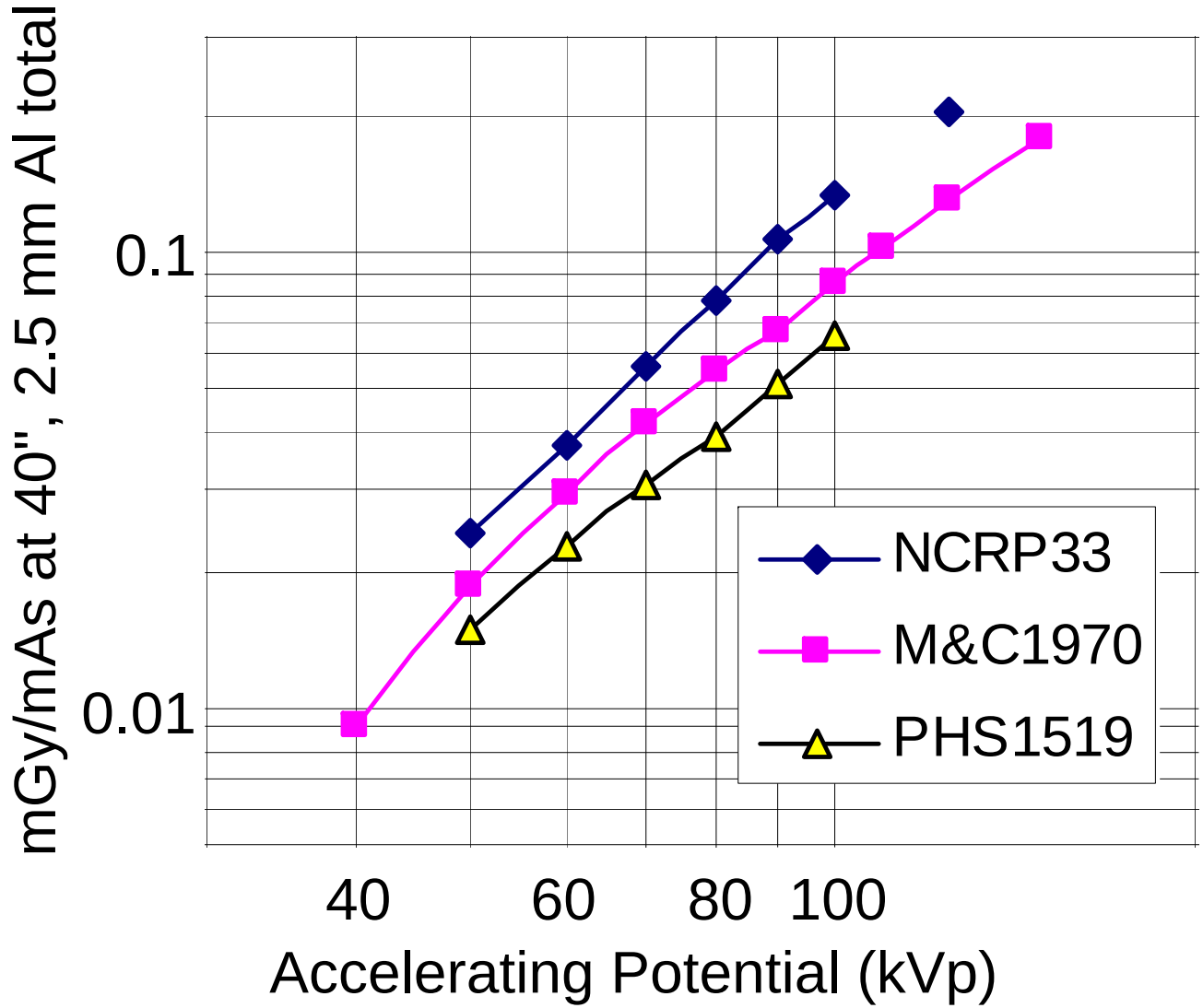
One site had a no collimation in 1970, resulting in a 99 cm circle at 178 cm SID

Organ or Tissue Dose due to Diagnostic X-ray Procedures Depends on

- Projection, e.g., anterior-posterior (AP) lumbar spine
- Degree to which the beam was collimated: ×1,000
- Actual or probable number of retakes: ×2
- Frequency of examination, e.g., annually : ×3
- Method used to assign doses: ×3 or more
  - Rosenstein 1976 (incarnated as ICRP Pub. 34, 1982)
  - Rosenstein 1988 http://www.fda.gov/cdrh/ohip/organdose.html
  - NRPB's SR-262 http://www.nrpb.org/publications/software/sr262.htm#r262
  - Finland's PCXMC http://www.stuk.fi/pcxmc/

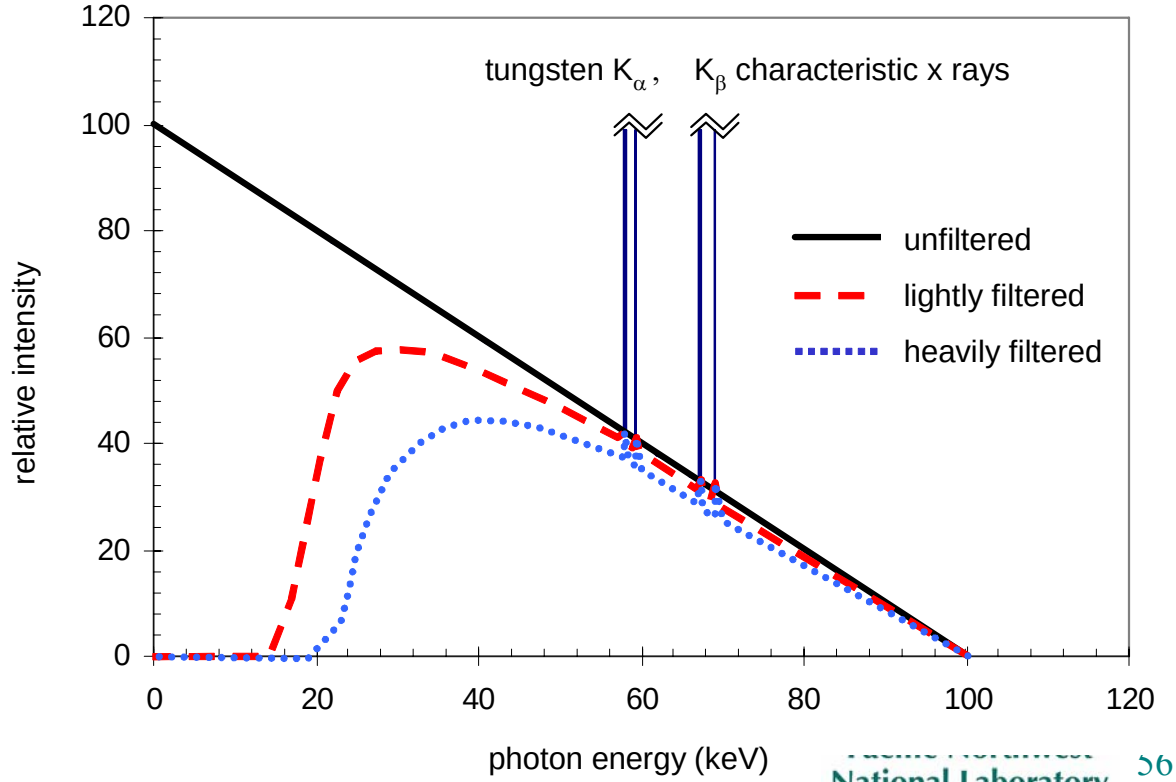
Variation of X-ray Output with Accelerating Potential

- Increases at $kVp^{>2}$ (Kramers 1923)
- Varies by more than a factor of 2 among authors



Effect of Inherent and Added Filtration

- More filtration: radiation is more penetrating
- Less filtration: radiation is less penetrating
- What is constant?
  - equivalent quality images; or
  - a fixed, known technique (kVp, mAs, SID) ?

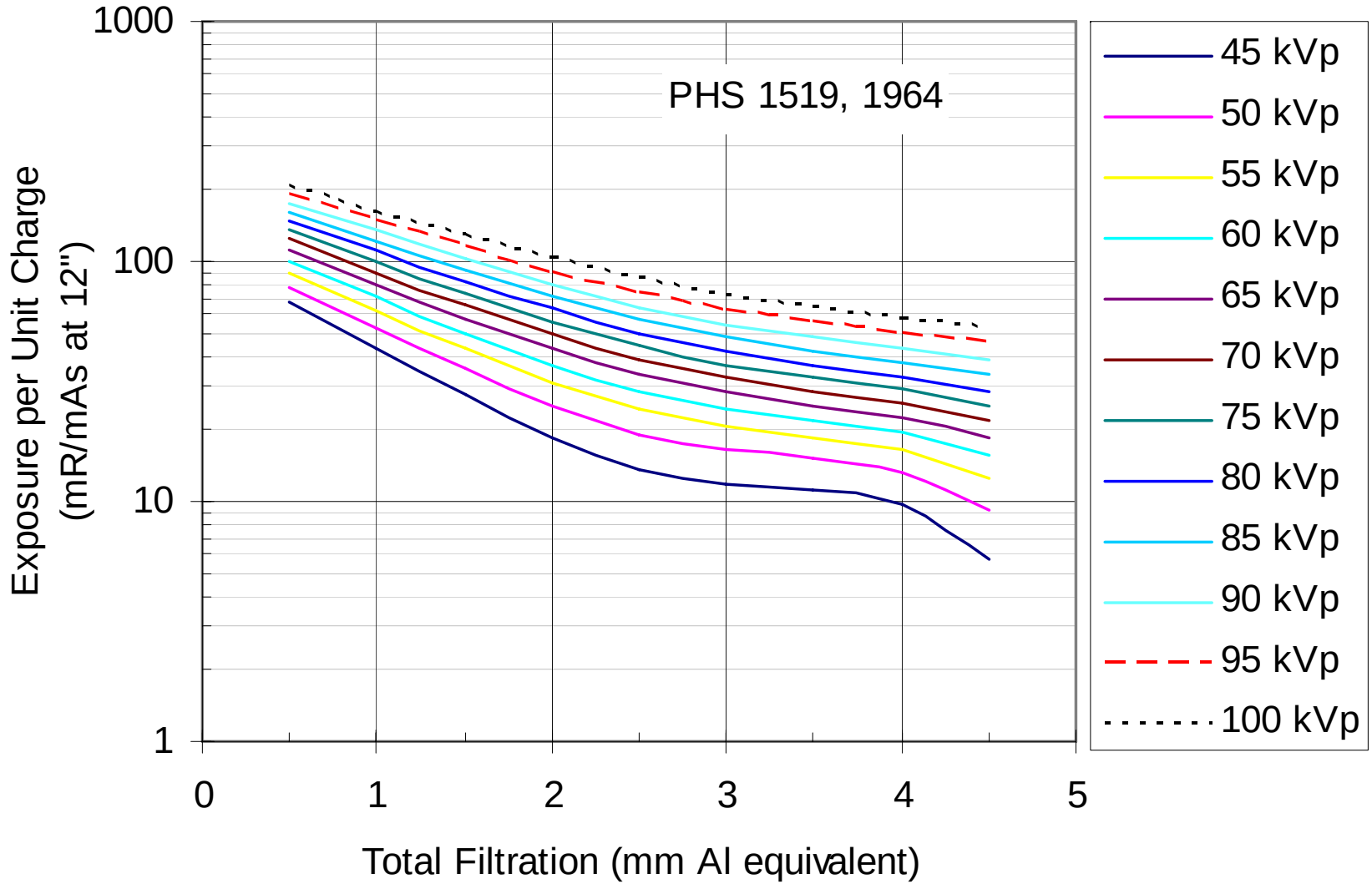


Effect of Inherent and Added Filtration

- More filtration: radiation is more penetrating
  - the ESE is lower for a given image quality
  - deeper tissues get a larger fraction of ESE
  - distal tissues get a larger fraction of ESE
- Less filtration: radiation is less penetrating
  - the ESE is higher for a given image quality
  - tissues in primary beam, especially those closer to the target, get higher doses than they would with more filtration
- Therefore, for equivalent quality images produced using an unknown technique, assuming
  - more filtration yields larger doses to distal tissues
  - less filtration yields larger doses to tissues in primary beam
- For a fixed, known technique (kVp, mAs, SID), assuming
  - more filtration results in lower doses to tissues in primary beam and higher doses to distal tissues
- Which assumption yields the highest dose per film depends on where the target tissue is!

Variation in X-ray Output with Accelerating Potential and Total Filtration

- Filtration changes output by ×4 (100 kVp), ×10 (45 kVp)

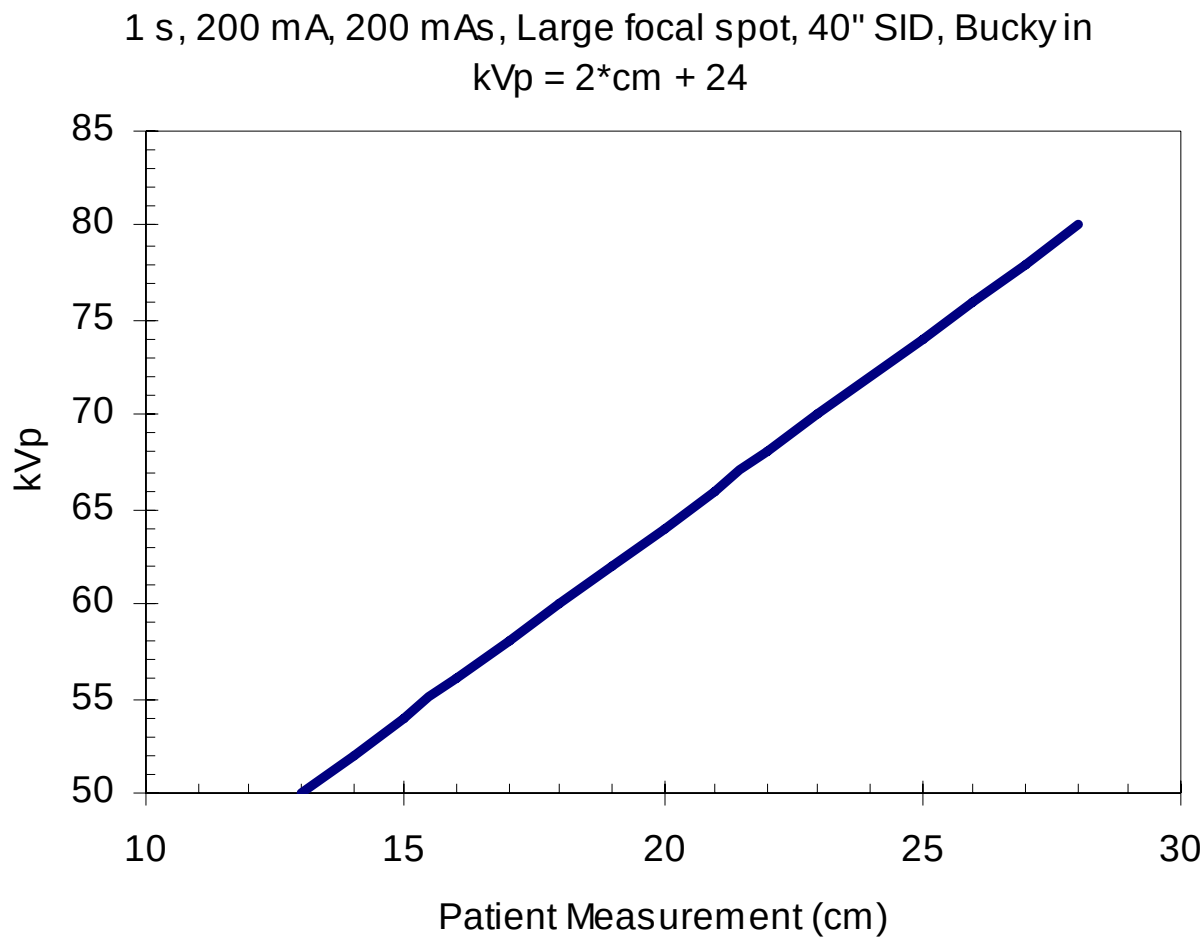


The Choice of Techniques Depends on

- Patient characteristics (i.e., thickness of the part X-rayed): ×3.5 for lumbar spine (LAT) with 36" SID
- The projection: You don't even get started without this!
  - Chest, Lumbar Spine, etc.
  - AP, LAT, PA, etc.
- Whether a Potter-Bucky moving grid was used: ×6
  - if so, the type of grid (focused or unfocused, grid ratio)
- The type of film or image receptor used
  - conventional radiography v. photofluorography: ×100
  - Film and screen combination (Bates 1969)
    - For a given screen, doses to produce O.D. = 1.0 range over a factor of 3.4, CV = 34%, GSD = 1.41
    - If screen is unknown, doses range over a factor of 15.2, CV = 67%, GSD = 2.04
- How the film was developed: ×2 or more

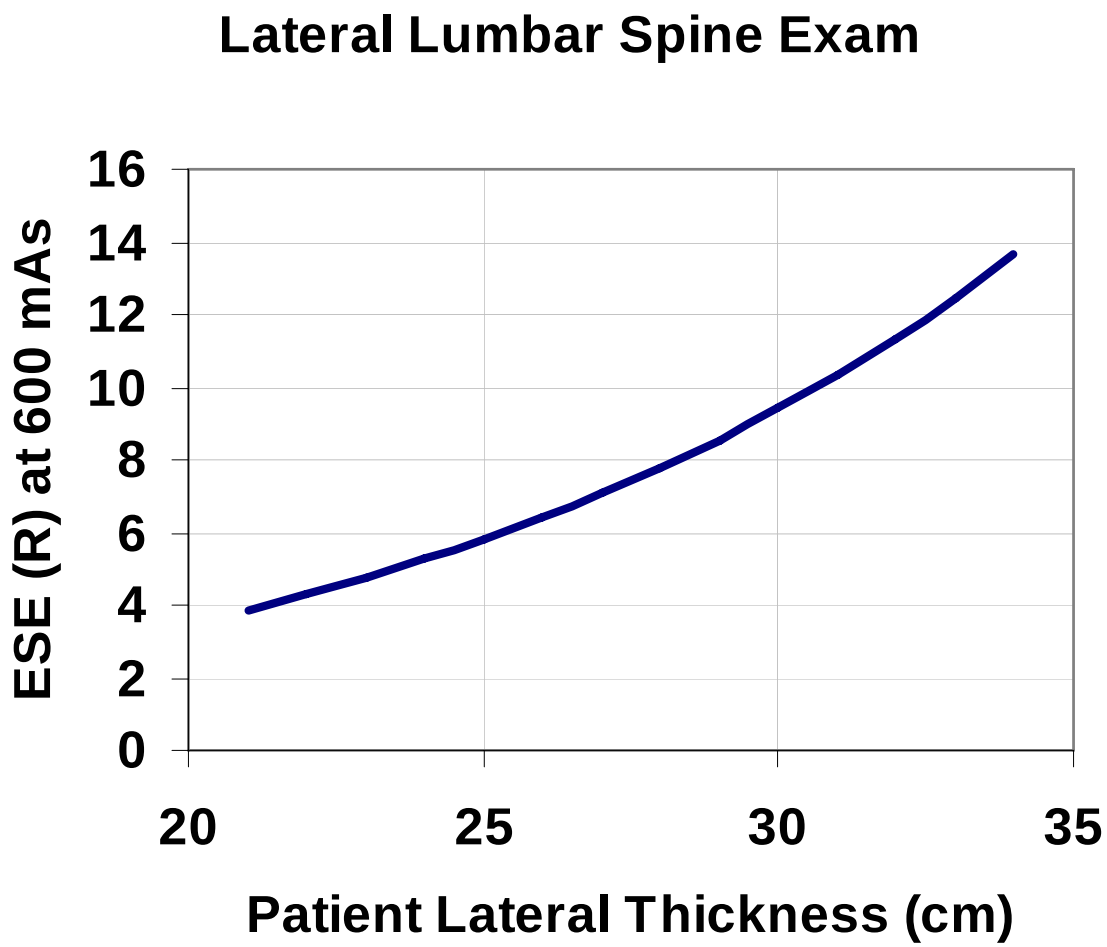
Effect of Patient Thickness

- More radiation and more penetrating radiation is needed to produce a quality image
  - generally, higher kVp is used



Effect of Patient Thickness

- Entrance skin exposure (ESE) can increase rapidly with thickness
  - For a given source-to-image distance (SID), the skin of a thicker patient is closer to the source
  - This is just geometry; it ignores the need for more radiation!
  - A factor of 3.5 for lumbar spine (LAT) with 36" SID



Effect of Collimation - 1

- This effect can be truly enormous
  - Tissues at edge of beam
  - Tissues partially in primary beam
  - Tissues not listed in old method
    - EEOICPA tissues do not correspond to
      - Rosenstein 1988 (CDRH web site)
      - U.K. National Radiological Protection Board (NRPB) SR-262
      - Finland's STUK PCXMC
      - Rosenstein 1976 (ICRP 34)

Cancers for Which Doses Might Be Needed: (This Doesn't Look Like ICRP's List!)

- Acute lymphoid leukemia
- All digestive
- All male genitalia
- All male genitalia AND All urinary organs (if male)
- Bladder
- Bone
- Breast
- Colon
- Esophagus
- Eye
- Female genitalia, less Ovary
- Female genitalia, less Ovary AND Ovary
- Female genitalia less Ovary And Ovary AND All urinary organs (if female)
- Gall bladder
- Leukemia, less CLL
- Leukemia, less CLL AND Acute lymphoid leukemia, AND Acute myeloid leukemia
- Leukemia, less CLL AND Acute myeloid leukemia
- Liver
- Lung
- Lung AND Other respiratory
- Lymphoma and multiple myeloma
- Malignant melanoma
- Malignant melanoma AND non-melanoma skin
- Malignant melanoma AND Non-melanoma skin-Basal cell
- Nervous System
- Non-melanoma skin-Basal cell
- Oral cavity and pharynx
- Other and ill-defined sites
- Other endocrine glands
- Other Respiratory
- Ovary
- Pancreas
- Rectum
- Stomach
- Thyroid
- Thyroid AND Other endocrine glands
- Urinary organs less bladder

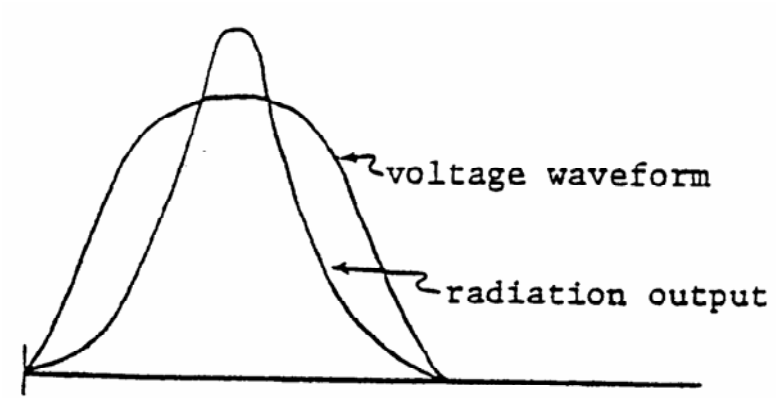
Adapted from Table 4, pp. 47-52, NIOSH-IREP Technical Documentation, June 18, 2002

Effect of Collimation - 2

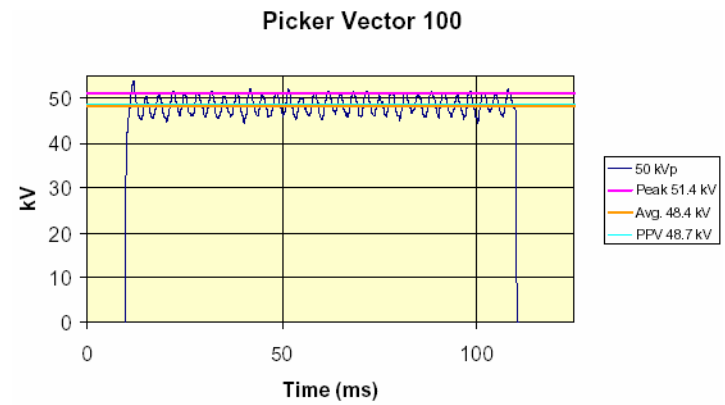
- This effect can be truly enormous (×1000) for tissues that were in the primary beam but were assumed not to be!
- Example at one facility in 1970
  - circular cone, not rectangular
  - measured beam diameter = 99 cm at 178 cm SID
  - a 36 cm × 43 cm (14” × 17”) film requires 56 cm
  - 99 cm includes head, gonads, and all of abdomen
- Standard methods of dose assessment are *worthless* for this collimation
  - Rosenstein 1976 (=ICRP Pub. 34)
  - Rosenstein 1986
  - NRPB SR 262
- Only STUK’s PCXMC can handle this

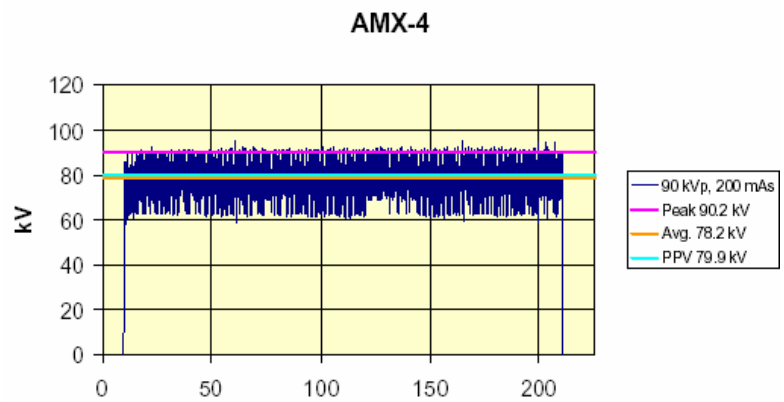
Effect of Waveform

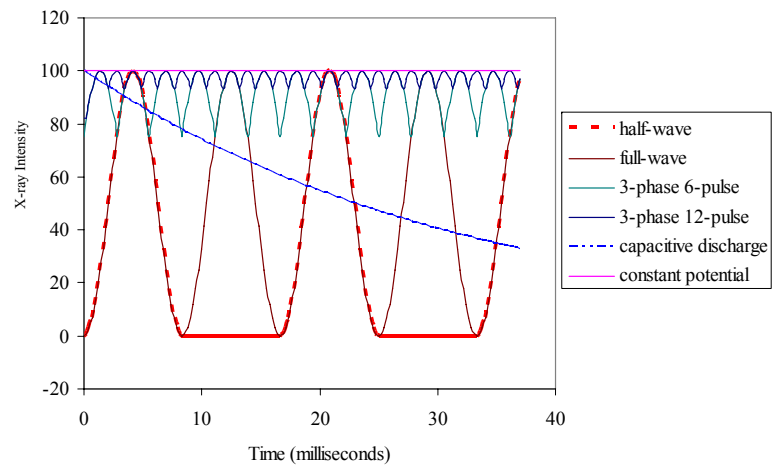
- For single-pulse (full-wave or half-wave rectified) x-ray generators, most of the dose comes in sharp pulses due to kVp^2 an absorption of low-energy photons



- Small changes in kVp make a disproportionate change in radiation

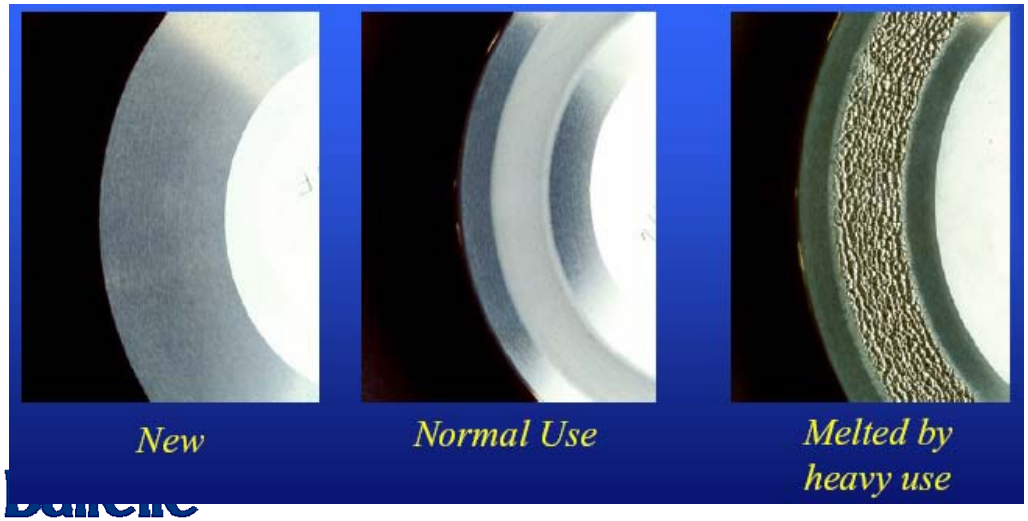


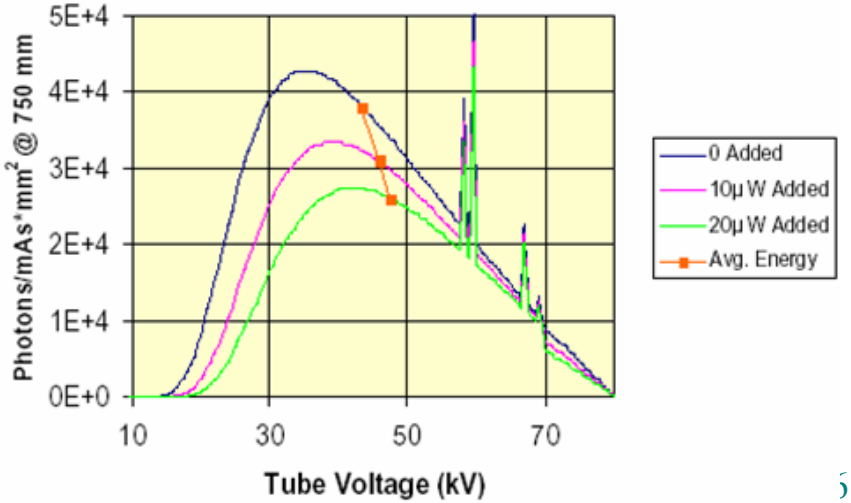




Film and Screen Combination; Film Quality and Developing; Anode Aging

- Film and screen combination (Bates 1969)
  - For a given screen, doses to produce O.D. = 1.0 range over a factor of 3.4, CV = 34%, GSD = 1.41
  - If screen is unknown, doses range over a factor of 15.2, CV = 67%, GSD = 2.04
- Film Quality
  - Poor quality has caused high doses
  - Exhausted chemicals cause high doses
- Anode aging: lower output, harder spectrum (Sunde 2004)





What Is Known and What Is Assumed

- Measurements can dramatically reduce uncertainty
  - Measurements don't apply to individuals
  - Individual variability still remains
- The existence of a usable film places limits on some parameters
  - doesn't tell about collimation, filtration, film/screen, retakes, patient thickness

X-Ray Dose Reconstruction Conclusions

- IF you know
  - trustworthy measurements were made
  - technics
  - film, screen, developer, collimation, filtration
  - patient thickness
  - projections, # of retakes

  you can limit some of the uncertainty
- IF you don't, it's doswaggery

Conclusions - 1

- What process produces a “dose” number?
  - Dosimetry: Uncertainty is dominated by what we measure
  - Dosinference: Uncertainty is dominated by what we don’t measure
    - consensus or expert inferential models
    - consensus or expert parameters of inferential models
  - Doswaggery: Uncertainty is dominated by what we make up (leaps of inference about what might have been)

Word Choice Based on Uncertainty

Term	Ratio of 97.5%^{ile} to 2.5%^{ile} of Inferred Dose
Dosimetry	**1.01 to 2**
Dosinference	**2 to 20**
Doswaggery	**>20**

Conclusions - 2

- Dosinference for Intakes
  - measurement: in vivo or in vitro bioassay, air monitoring
  - models and model parameters
- Dosinference (TNLD) or doswaggery (NTA film or job titles) for occupational neutron dose reconstruction
- Doswaggery for diagnostic x-ray dose reconstruction for tissues not imaged on the film
- **Not all "doses" result from dosi*metry*!**

Acknowledgment

- Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL0 1830

Disclaimer

- The opinions expressed above, if any, are mine alone and have not been reviewed or approved by Battelle, the Pacific Northwest National Laboratory, or the U.S. Department of Energy.

References

American National Standards Institute (ANSI). 2001. *Design of Internal Dosimetry Programs*. ANSI/HPS N13.39-2001, Health Physics Society, McLean, Virginia.

Bates, Lloyd M. Some Physical Factors Affecting Radiographic Image Quality: Their Theoretical Basis and Measurement. PHS Pub. No. 999-RH-38, August 1969.

Birchall A, AC James, and CR Muirhead. 1991. "Adequacy of Personal Air Samplers for Monitoring Plutonium Intakes." Radiation Protection Dosimetry 37(3):179-188.

BRH (Bureau of Radiological Health), 1979, Analysis of Retakes: Understanding, Managing, and Using Analysis of Retakes Program for Quality Assurance, HEW Publication (FDA) 79-8097, U.S. Department of Health, Education and Welfare, Public Health Service, Food and Drug Administration, Washington, D.C.

Gitlin, J. N., and P. S. Lawrence, 1966, Population Exposure to X-Rays, U.S., 1964, Report No. 1519, U.S. Government Printing Office, Washington, D.C.

Health Physics Society (HPS). 1996. *Performance Criteria for Radiobioassay. An American National Standard*. HPS N13.30-1996, Health Physics Society, McLean, Virginia.

ICRP (International Commission on Radiological Protection), 1982, "Protection of the Worker in Diagnostic Radiology," Annals of the ICRP, ICRP Publication 34, 9(2/3):1-82.

International Commission on Radiological Protection (ICRP). 1993. "Protection Against Radon-222 at Home and at Work. ICRP Publication No. 65." Annals of the ICRP 23(2).

International Commission on Radiation Units and Measurements (ICRU). 1998. Fundamental Quantities and Units for Ionizing Radiation. ICRU Report No. 60, ICRU Publications, Bethesda, Maryland.

International Organization for Standardization (ISO). Guide to the Expression of Uncertainty in Measurement. Geneva; 1995. Available as NIST Technical Note 1297 at http://physics.nist.gov/cuu/Uncertainty/index.html

Kramers, H.A., 1923, [Title not available], Phil. Mag. 46():836.

References

NCRP (National Council on Radiation Protection and Measurements), 1968, Medical X-Ray and Gamma-Ray Protection for Energies Up To 10 MeV, Report No. 33, Washington, D.C.

NRPB (National Radiological Protection Board). "Normalised Organ Doses for Medical X-Ray Examinations Calculated Using Monte Carlo Techniques," NRPB's SR-262 http://www.nrpb.org/publications/software/sr262.htm#r262 .

Potter CA. Intake Retention Fractions Developed from Models Used in the Determination of Dose Coefficients Developed for ICRP Publication 68 - Particulate Inhalation. Health Phys 83(5):584-789; 2002.

Reissland JA. 1982. "Epidemiological Methods of Assessing Risks from Low Level Occupational Exposure to Ionizing Radiation." Radiation Protection Dosimetry 2:199-207.

Rosenstein, M., 1976, *Organ Doses in Diagnostic Radiology*, HEW Publication (FDA) 76-8030, Bureau of Radiological Health, Rockville, Maryland.

Rosenstein, M., 1988, *Handbook of Selected Tissue Doses for Projections Common in Diagnostic Radiology*, FDA 89-8031, U.S. Dept of Health and Human Services, Washington, DC.

Scott BR, MD Hoover, and GJ Newton. 1997. "On Evaluating Respiratory Tract Intake of High-Specific Activity Emitting Particles for Brief Occupational Exposure." Radiation Protection Dosimetry 69(1):43-50.

Strom DJ. 1994. "Programs for Assessment of Doses from Intakes of Radioactive Materials." Chapter 25 in *Internal Radiation Dosimetry*, ed. OG Raabe, pp. 543-50. Medical Physics Publishing, Madison, Wisconsin.

Strom DJ. "Dosimetry, Dosinference, and Doswaggery." Radiation Protection Dosimetry 98(4):363-366; 2002.

Strom DJ and CR Watson. 2002. "On Being Understood: Clarity and Jargon in Radiation Protection." Health Physics 82(3):373-386.

STUK (Finnish Center for Radiation and Nuclear Safety). July 14, 2002. PCXMC: Monte Carlo X-Ray Program, Version 1.5 http://www.stuk.fi/pcxmc/.

Sunde, P. 2004. Diagnostic X-ray Dose & KVp Instrumentation Review & Tips. http://www.radcal.com Monrovia, California: Radcal Corp,

Taylor BN, Kuyatt CE. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297 http://physics.nist.gov/cuu/pdf/tn1297.pdf . Gaithersburg, MD 20899: National Institute of Standards and Technology, Physics Laboratory; 1994.