Determining the dose outside the treatment field

Stephen F. Kry, PhD

Workshop on Risk of secondary cancer following radiotherapy

September 9, 2016

THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History®

How do we determine stray radiation dose?

1. Dose assessment
    1. *Treatment planning system*
    2. *Measurement*
    3. *Neutrons*
    4. *Monte Carlo*
2. Dosimetric assessment for radiation epidemiology studies
    1. *Individual dosimetry*
    2. *Reference cases*

1. Dose assessment

- See upcoming AAPM report:

Task Group 158
Measurement and Calculation of Doses Outside the Treatment Volume from External-beam Radiation Therapy

Stephen Kry, Bryan Bednarz, Rebecca Howell, Larry Dauer, David Followill, Eric Klein, Harald Paganetti, Brian Wang, Cheng-Shie Wuu, X. George Xu.

- Approved by AAPM, publication pending in *Medical Physics*

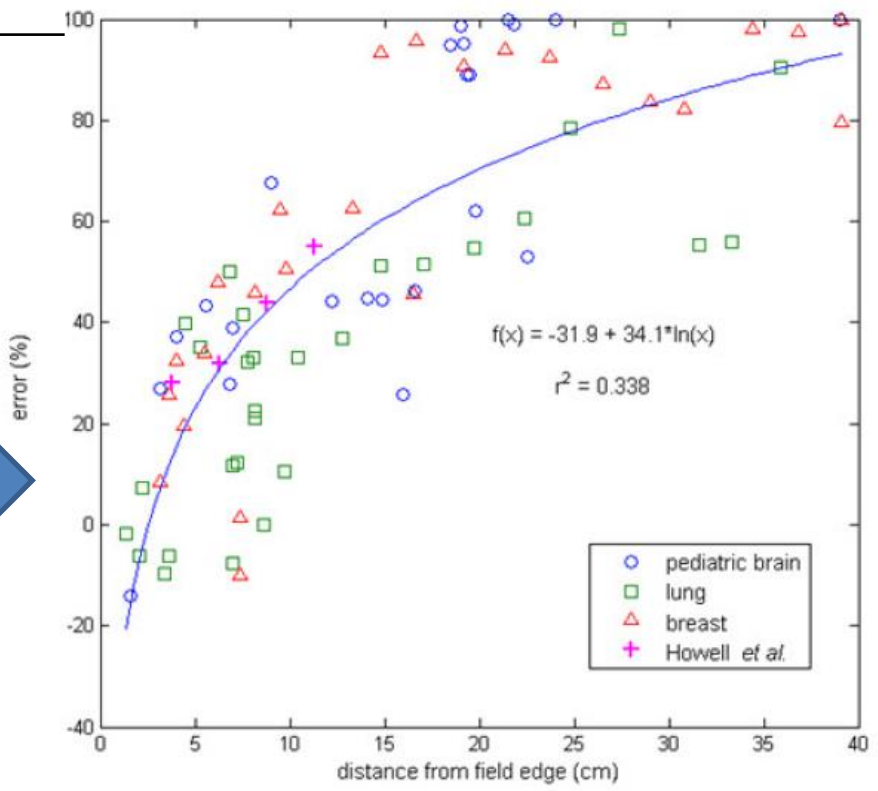
1.1 TPS accuracy outside the treatment field

Distance from Field Edge (cm)	D_{calc} (cGy)		D_{meas} (cGy)		Percent Difference
3.75	3.08	0.61	4.24	0.45	**38%**
6.25	2.02	0.43	3.01	0.24	**49%**
8.75	1.16	0.32	2.09	0.14	**80%**
11.25	0.66	0.33	1.49	0.13	**126%**

Howell et al, 2010

- Poor accuracy even close to the field
- This is for a simple, conventional field.

- Not an easier calculation with complex contemporary fields
- Again, poor agreement
- Consistently **underestimates** dose



Huang et al, 2013

1.1 TPS guidelines

- Beyond 3 cm from field edge

  or

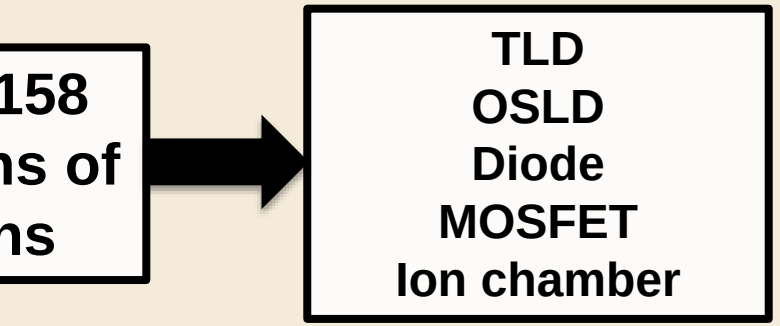
- Below 5% isodose line

- Don’t expect the TPS to give you the right answer

1.2 Out-of-field Photon Measurements

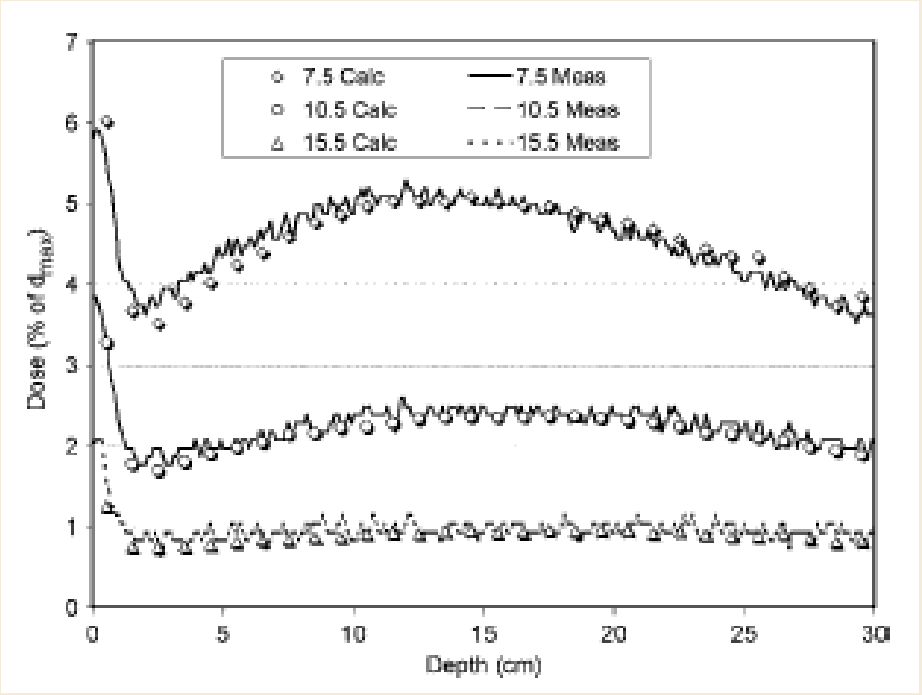
- 4 general measurement considerations that are particularly relevant to out-of-field measurements:
  1. Dosimeter dynamic range – must be able to get sufficient signal (can be easy with phantom – scale MU)
  2. Dose at the surface,
  3. Energy spectrum,
  4. Presence of other particles.

For various dosimeters, TG-158 considers specific implications of measurement considerations



1.2 Out-of-field Measurements
Dose at the Surface

- Outside the treatment field, the superficial dose is increased by stray electrons, so there is a build-down effect instead of a build-up effect at the surface.
  - The dose is 2-5x higher at the patient surface, and decreases to ~ d_{max}, below which the dose becomes ~ constant with depth.
  - If a dosimeter is placed on the patient surface, it will overestimate the dose (by 2-5x).
  - Dosimeter should be covered by bolus of a thickness of ~ $d_{max.}$



1.2 Out-of-field Measurements
Energy Spectrum Considerations

- The average beam energy is much lower outside the treatment field. (0.2-0.5 MeV vs 1.5 MeV)
- A dosimeter that is not tissue equivalent will over-respond to this softer radiation relative to its calibration, which will generally be based on the 1º beam.
  - This effect can be sizeable to the point of unacceptable accuracy unless it is accounted for.

TLD/OSLD	Diode	MOSFET	Ion Chamber
• Overresponse **2-12%/5-30%** compared to in-beam.	• Overresponse **up to 70%** compared to in-beam.	• Overresponse **50 to 600%** compared to in-beam.	• Overresponse **negligable,** compared to in-beam.

1.2 Out-of-field Measurements
Other Particle Considerations

- It is important to know and consider if measurements are being made in a mixed field
  - Dosimeters can respond very differently to different types of radiation.

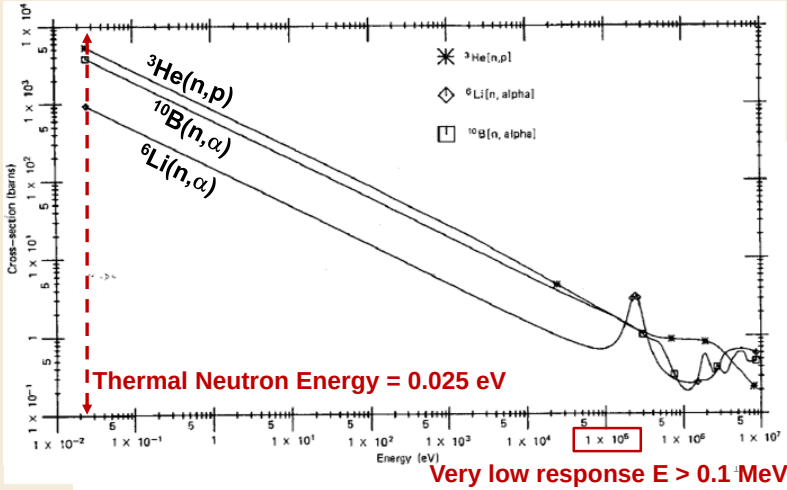
TLD-100: LiF:Mg,Ti

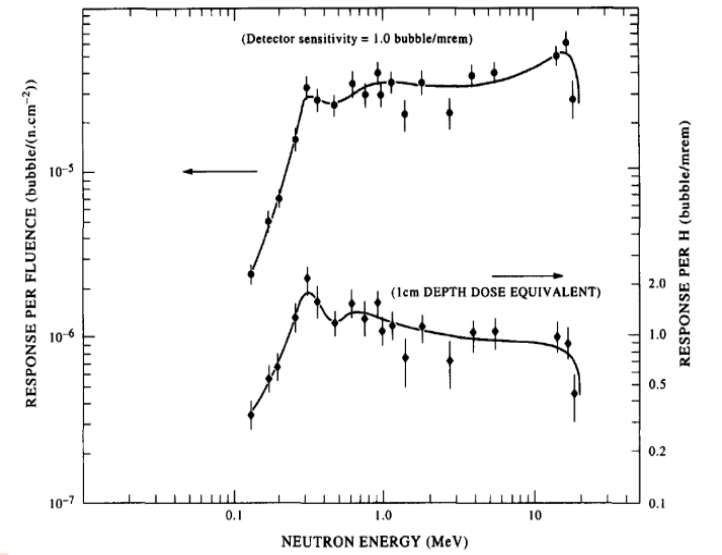
- The standard TLD-100 overresponds to neutrons by as much as 10-12x (compared to photons).
  - A neutron-insensitive dosimeter (such as TLD-700) should be used to measure photon doses (for >10 MV).
  - separate neutron dosimetry should be conducted to determine the neutron dose.

Knoll, 2010

1.3 Neutron Dosimetry

- **Neutron detectors exhibit strong energy dependence.**
- **Thermal neutron detectors.**
  - Passive detectors, e.g., TLD-600, ^{197}Au activation foils
  - Active detectors, e.g., ^{3}He, ^{10}B, ^{6}Li
- **Fast neutron detectors.**
  - Bubble detectors
  - Track etch detectors
  - Thermal neutron detectors within moderators, e.g., Bonner spheres, commercial rem-meters, etc.

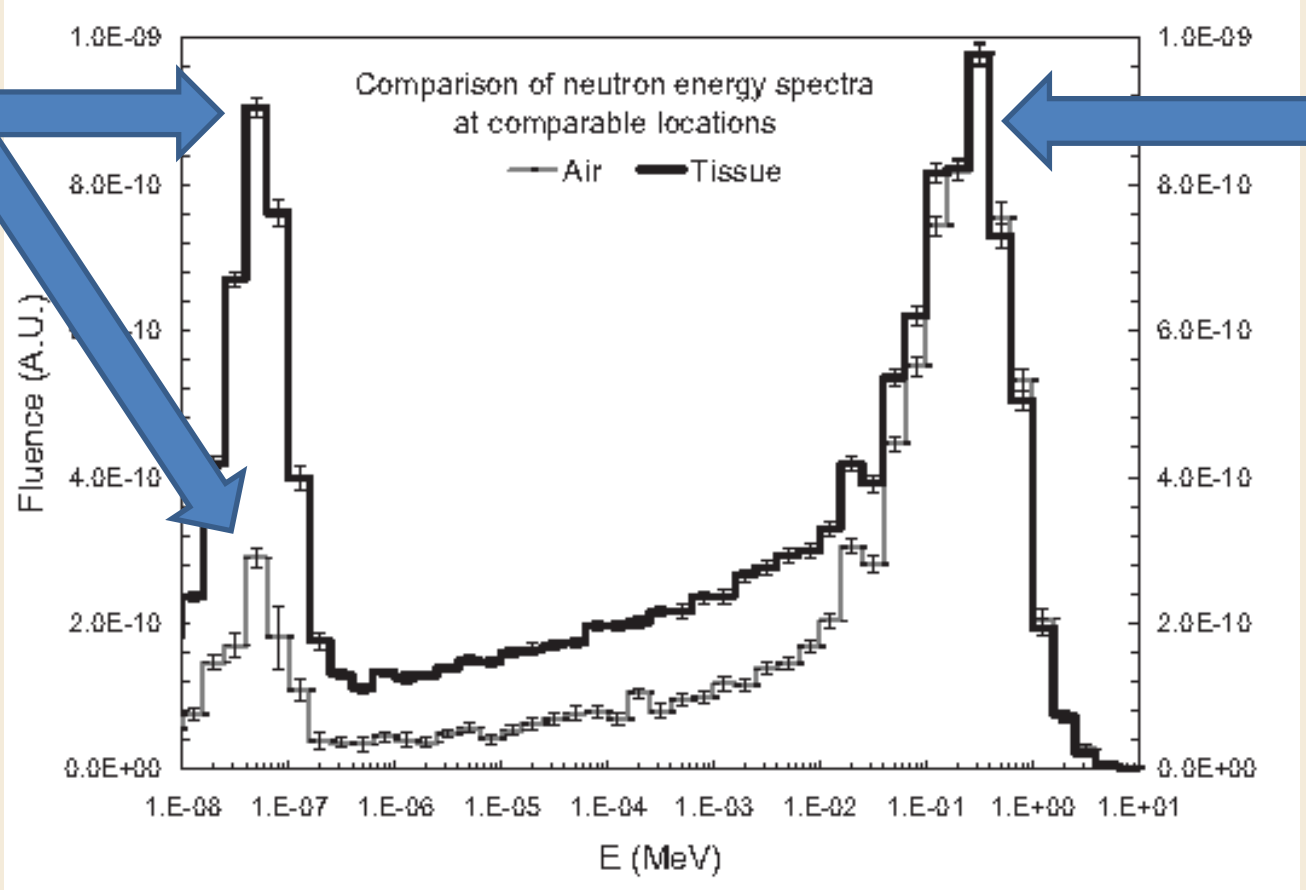




1.3 Neutron Dosimetry Challenges

- The neutrons depositing dose are not generally the neutrons generating signal
- The relationship between these is NOT constant

Signal

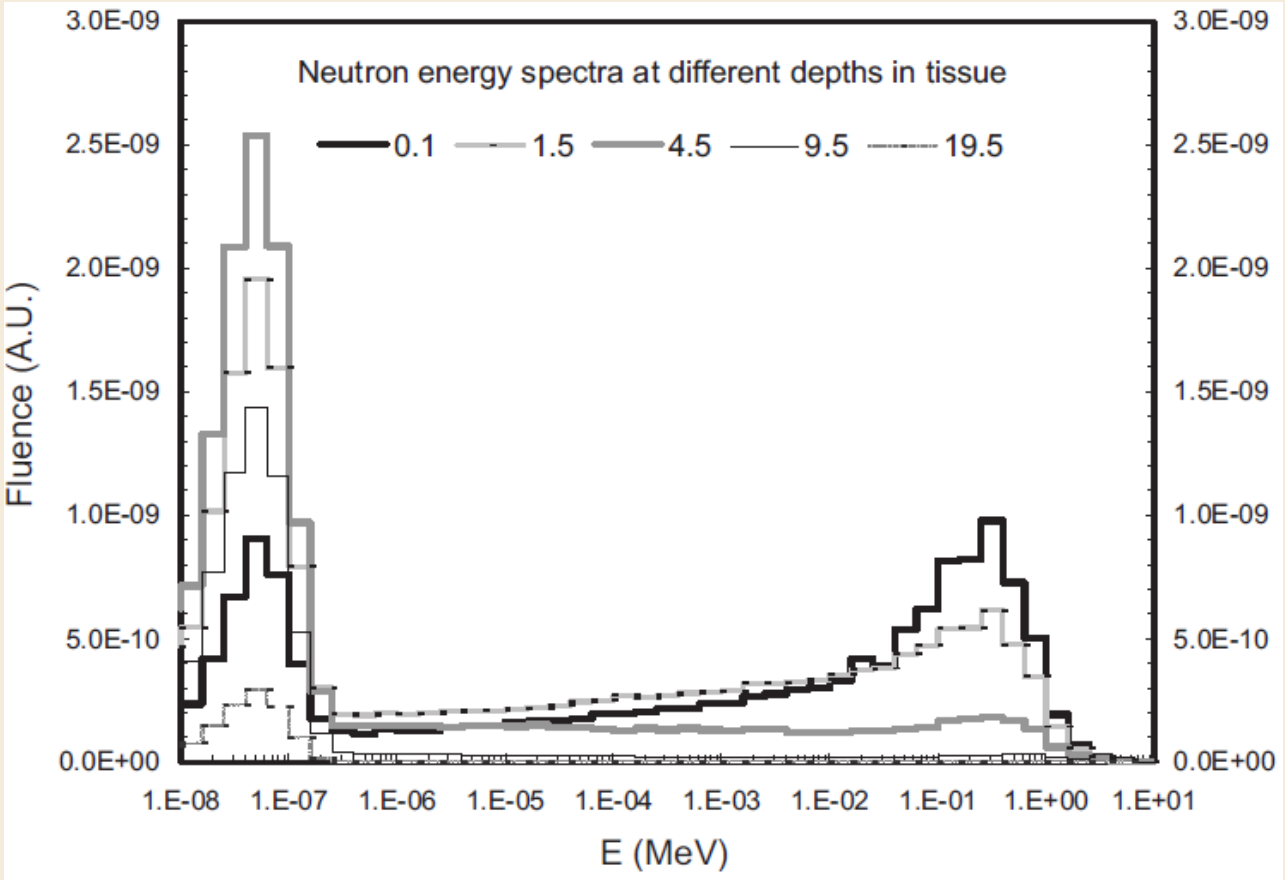


Dose

Kry *et al.* 2009

1.3 Neutron Dosimetry Challenges Phantom/Patient Measurements

- Spectrum changes dramatically and rapidly
- Can't apply a single calibration factor = **hard**



Kry *et al.* 2009

1.3 Neutron Dosimetry: Measurements

- Neutron dosimetry is very challenging.
- It is essential to know the spectrum you're trying to measure, and to account for any differences between this spectrum and the calibration spectrum in terms of the response of the detector.
  - Hard – requires lots of information
  - Not small errors
- In vivo/in phantom measurements are extremely challenging.
- May rely on well vetted literature.

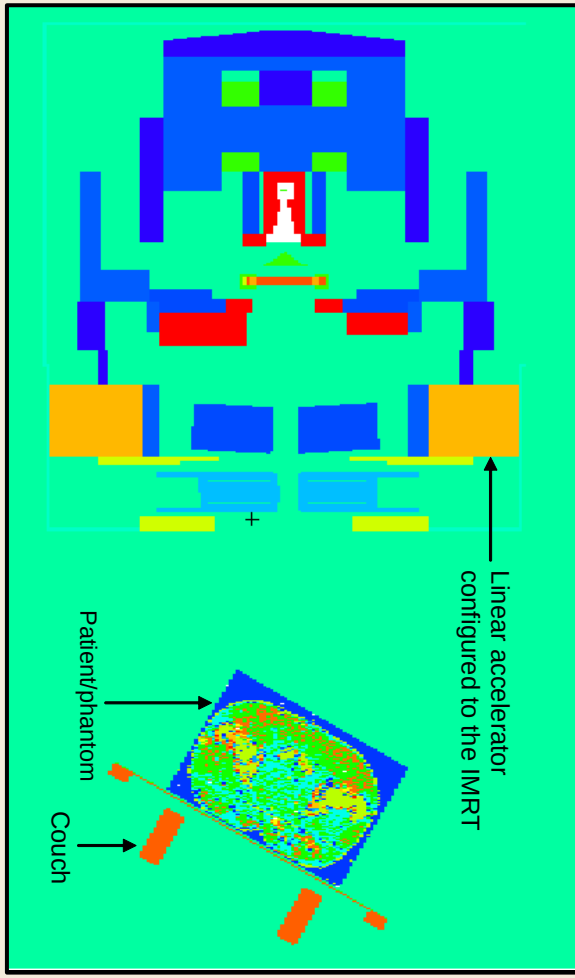
1.3 Neutron Dosimetry: Measurements

- Neu
- It is ing to me bet ectrum in t
  - H
  - N
- In v nely cha
- Ma

1.4 Monte Carlo Photon simulations

- Can be done and provide accurate dosimetry
  - Particularly when coupled with anatomically realistic phantom
- Just a Beam-line model:
  - Accurate to ~15 cm from field edge
- Detailed head model:
  - Accurate through entire patient

- Requires detailed validation
- Not fast
- IMRT treatments may mean hundreds of individual fields to run



1.4 Monte Carlo
Neutron production from x-ray therapy

- Easier simulation to calculate neutrons
  - Energy cutoff higher = faster
  - Expected precision is typically lower
- Model the entire linac head
  - Good within 10-20%
- Simple model of linac head
  - Good within ~40%
- Just beam-line components
  - Errors of 2-3 times. Don’t do this.
- Validate model against good quality measurements (usually in air)

1. Summary

- There are several methods for assessing dose outside the treatment field
- Each one has challenges and potential pitfalls to avoid!

- Neutron dosimetry is most challenging
- Neutrons are typically a small component of dose equivalent (10-20%)
  - Ignored in epidemiologic studies

TODAY'S TOPICS

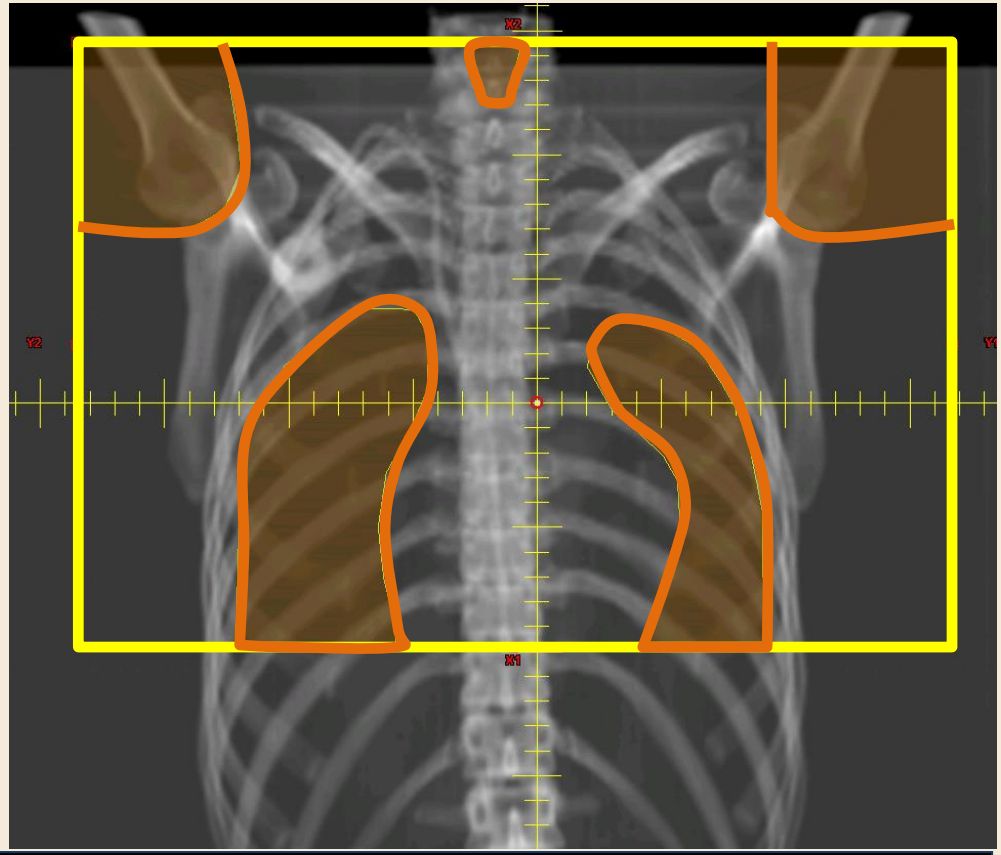
1. Dose assessment
    1. *Treatment planning system*
    2. *Measurement*
    3. *Neutrons*
    4. *Monte Carlo*
2. Dosimetric assessment for radiation epidemiology studies
    1. *Individual dosimetry*
    2. *Reference cases*

2. Dosimetric input for radiation epidemiologic studies

- This sounds very similar
  - Assess the dose to an organ of interest
  - Report it for epidemiologic consideration!
- Actually there are some very different considerations
  1. Nature of available information
  2. Quality of available information
  3. Specifics of desired information
- Must be able to implement on a large scale (1000's of patients)

2. Nature of Available Information

- Type of radiotherapy
- Total therapeutic dose
- Dose per fraction
- Number of beams
- Beam orientation
- Beam energy
- Radiograph with field geometry(s)



- What's not in the treatment record?

Stray radiation dose

Height/weight, location of organs/second cancers….

2. Nature of Available Information

- Most important detail in determining radiation dose: Distance from field edge
- Where does the field extend?
  - Treatment record might have DRR/port film (rarely)
  - Might have drawing. Or vague description. Or nothing.
  - Compare this with
    - Where you think the organ is
    - Separate record that has location of the tumor marked with an “X”
  - In field (100%)? On the edge (50%)? Near (10%)?
  - This transition can take only 5 cm
  - This size scale is hard to resolve if you have the patient in front of you!!

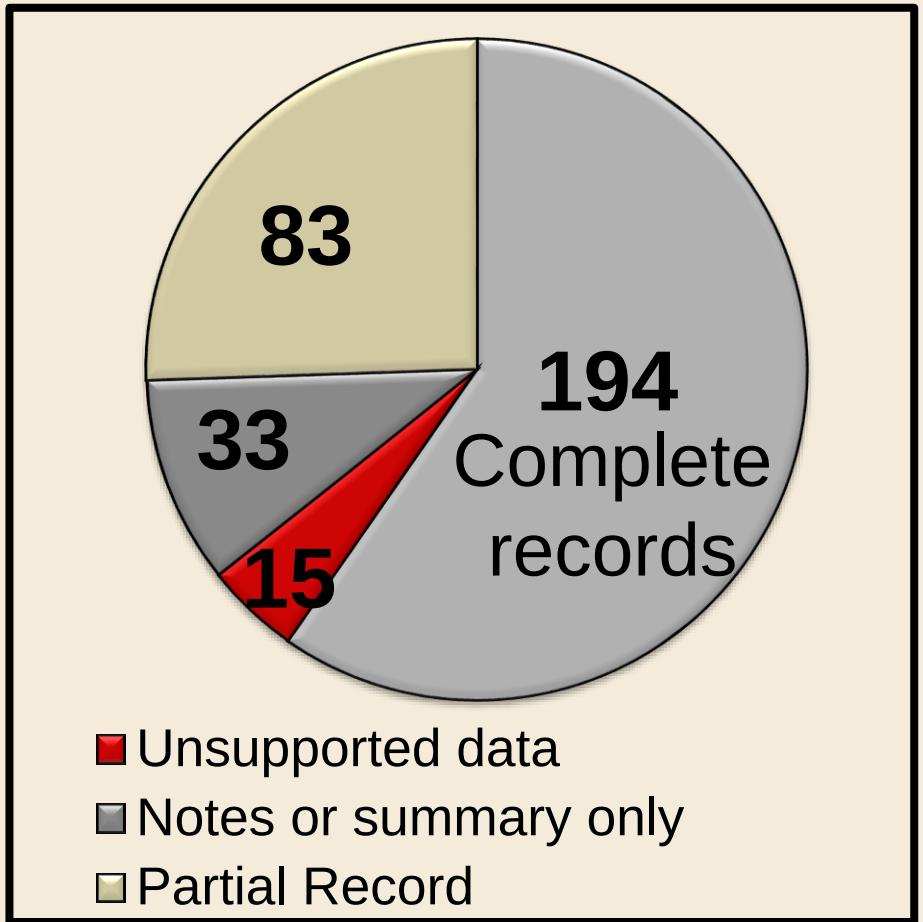
2. Nature of Available Information

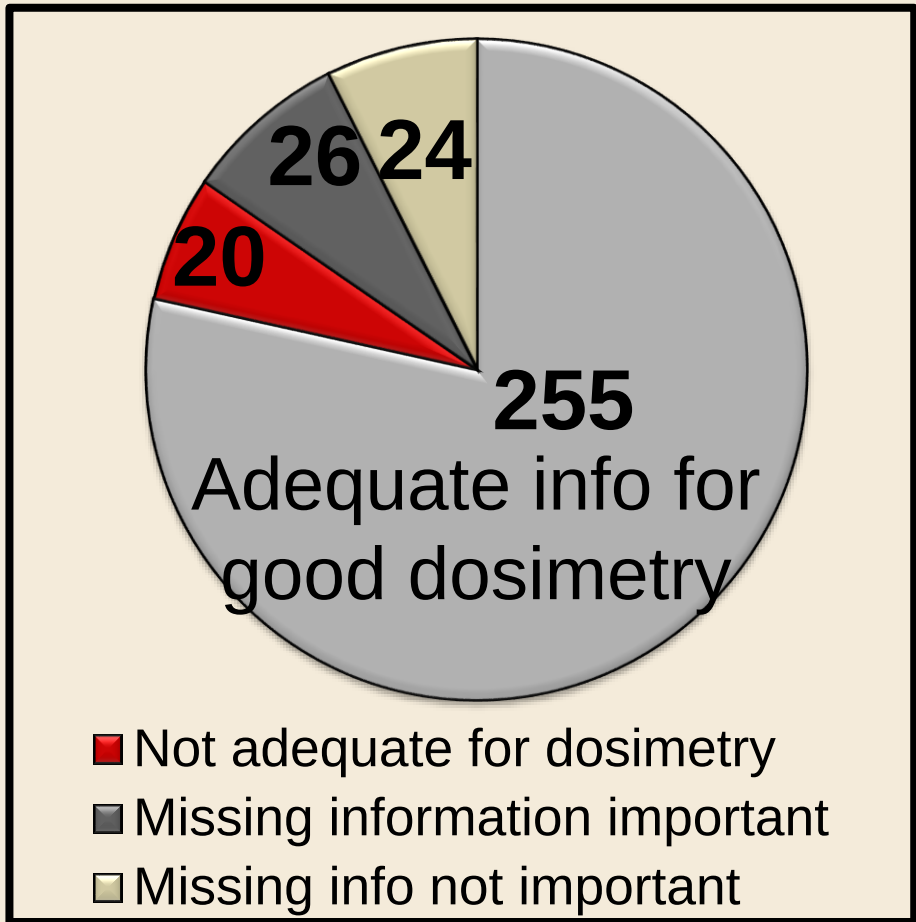
- Might know actual size of treatment field
  - But how tall is the patient (not in patient charts, just age)?
  - What anatomy does this cover?
- Historical treatments and multi-institutional studies show a lot of variability in terms of how fields are applied – hard to make assumptions about tx.
- Messy!!!!

2. Quality of Available Information
Is data even present?

- **RT data received** **RT information quality**

n=325





2. Nature of Desired Information

- Imagine the epidemiology study is concerned with stomach cancers after RT.
- What is the dose to the stomach?
  - If the stomach is partially inside the treatment field, the dose to different parts of the stomach will be dramatically different!
    - Mean dose? Max dose?
    - Where does the tumor originate?
- Say we generate a DVH for the stomach
  - This assumes the stomach is in the “usual” place and has the “usual” shape. This isn’t a particularly good assumption.

TODAY'S TOPICS

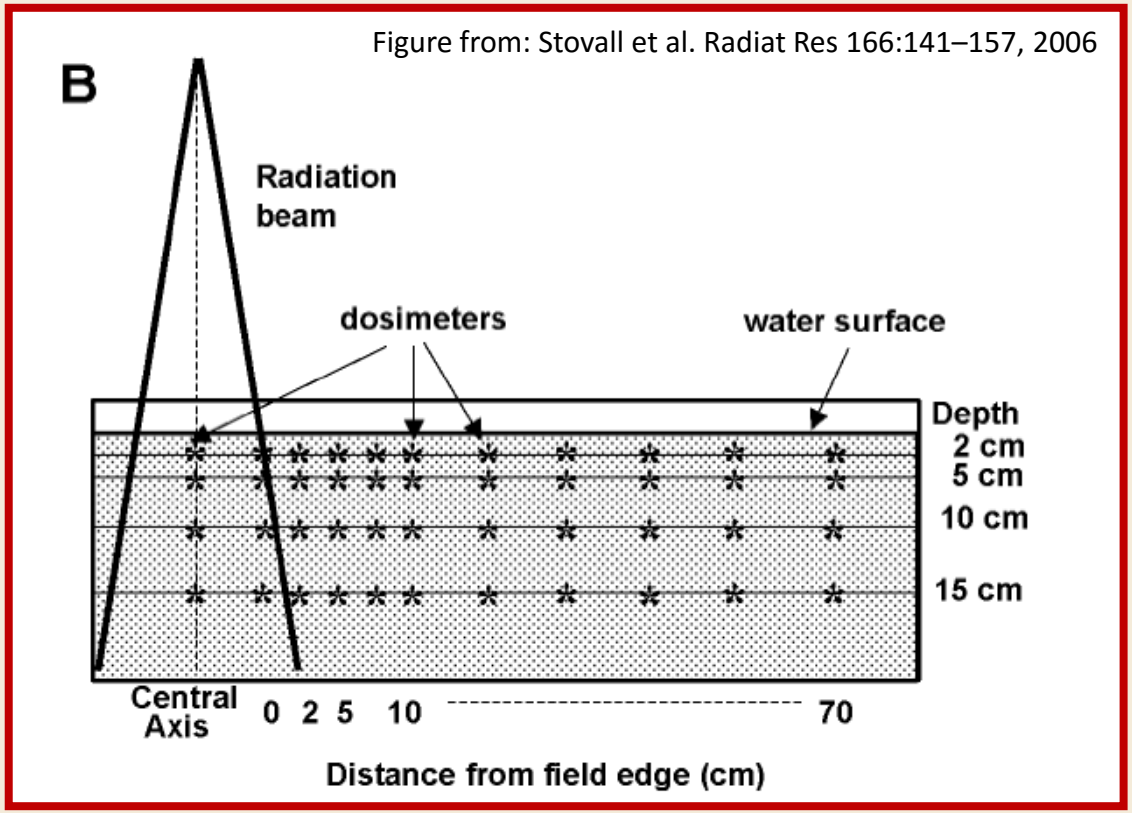
1. Dose assessment
    1. *Treatment planning system*
    2. *Measurement*
    3. *Neutrons*
    4. *Monte Carlo*
2. Dosimetric assessment for radiation epidemiology studies
    1. *Individual dosimetry*
    2. *Reference cases*

2.1 Individual Dosimetry

- Dosimetry for each patient case is managed and calculated individually
- Combing an analytic dosimetry model
  - Estimates dose at a given location from a given treatment field
- And a generic phantom
  - Relates geometry of tx field and location of interest
- This approach has been used for hundreds of RT-epidemiologic studies (Dr. Stovall)
  - CCSS, REB, WeCare, St. Jude life, ….

2.1. Analytical Model of Out-of-Field Dose

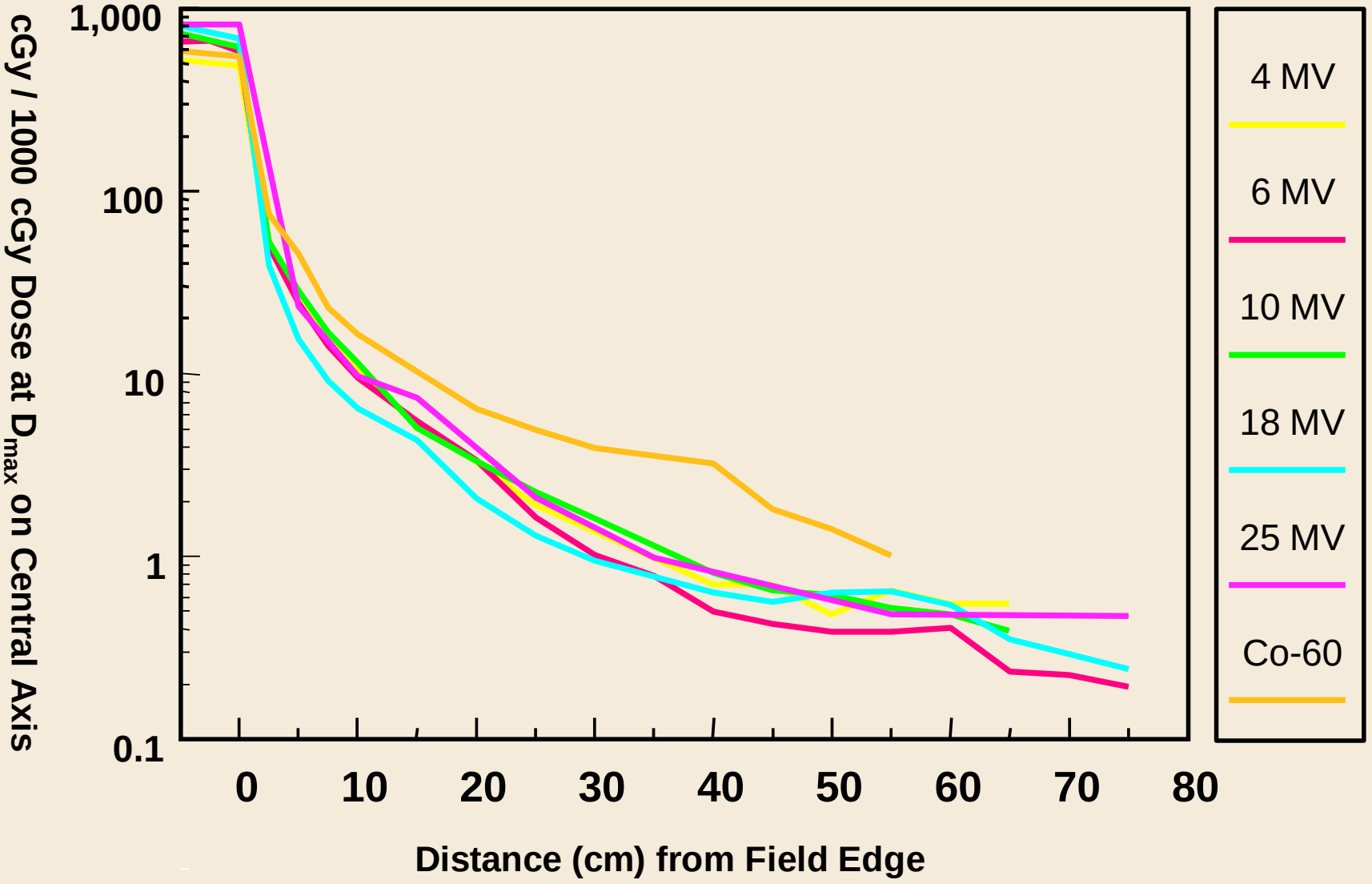
- Dose outside the treatment beam measured in large water phantom
  - Various beam energies and field sizes.



Data fit to analytical models to derive doses at specified distances from different fields

2.1 Model for total Absorbed Dose from Treatment Beams

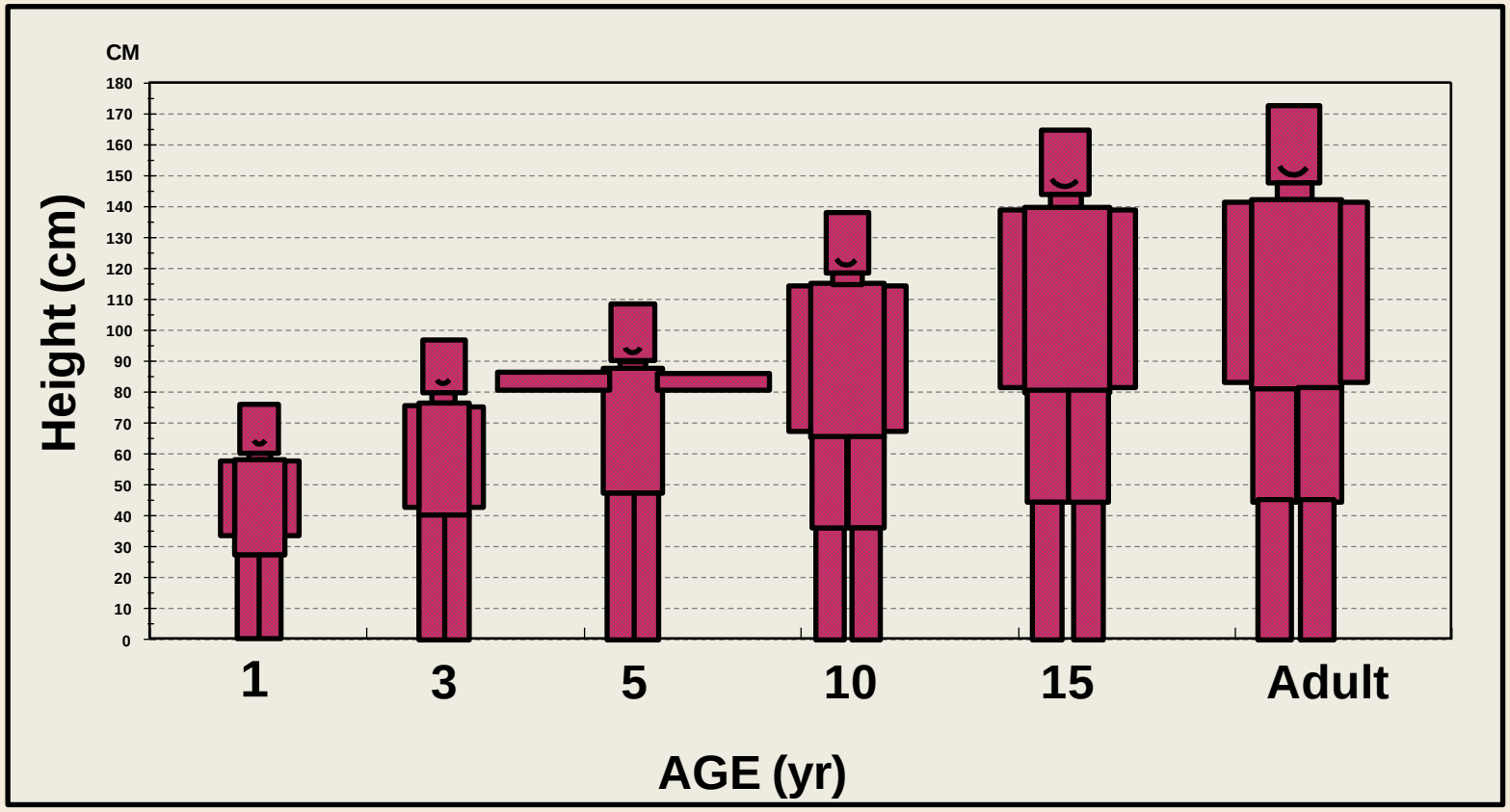
10x10 cm² Field Size - Various Energies



2.1 Mathematical Phantoms

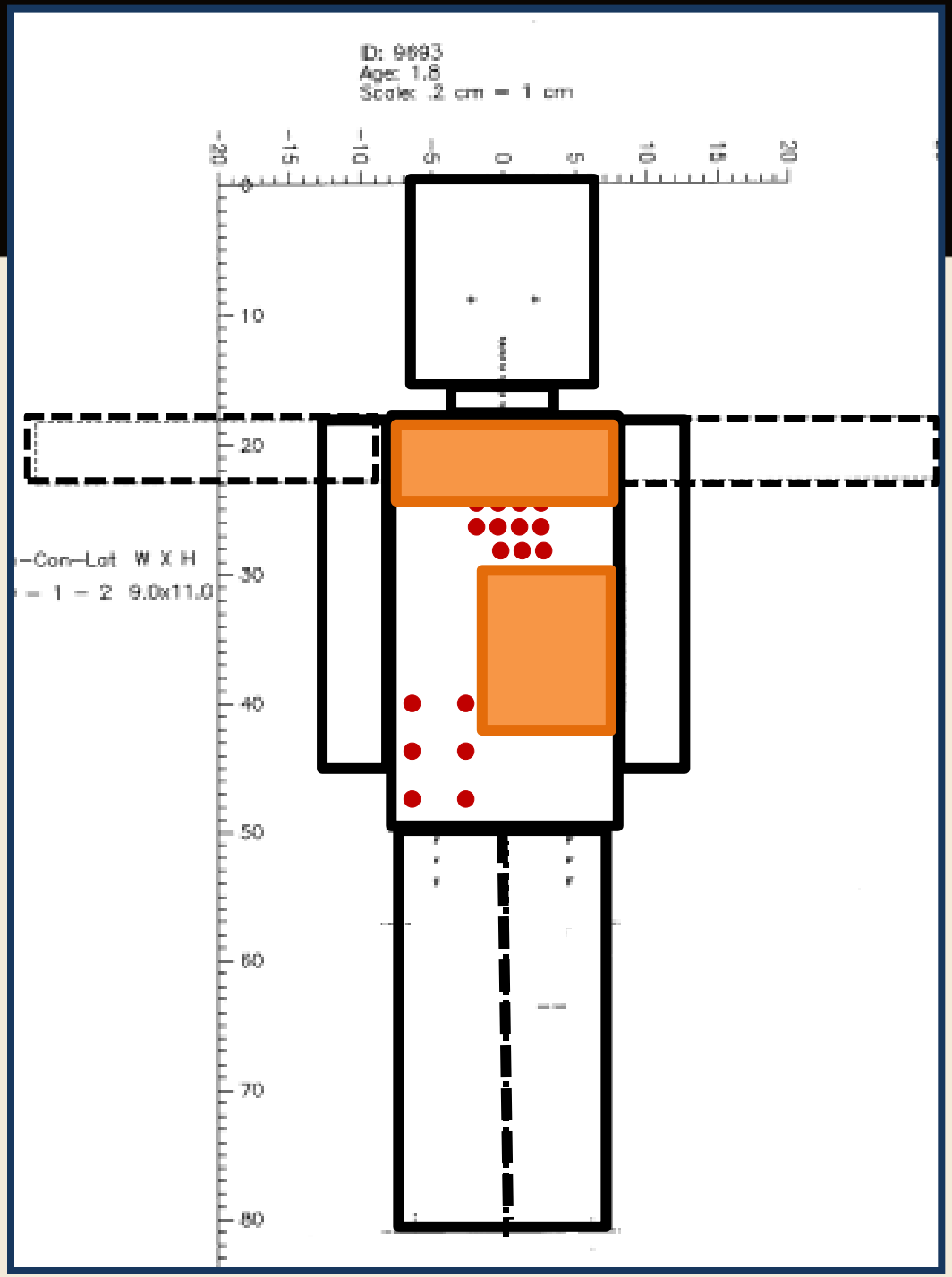
- Phantom size can be modified to represent patient of any age.

Figure from: Stovall et al. Radiat Res 166:141–157, 2006



2.1 Mathematical Phantom

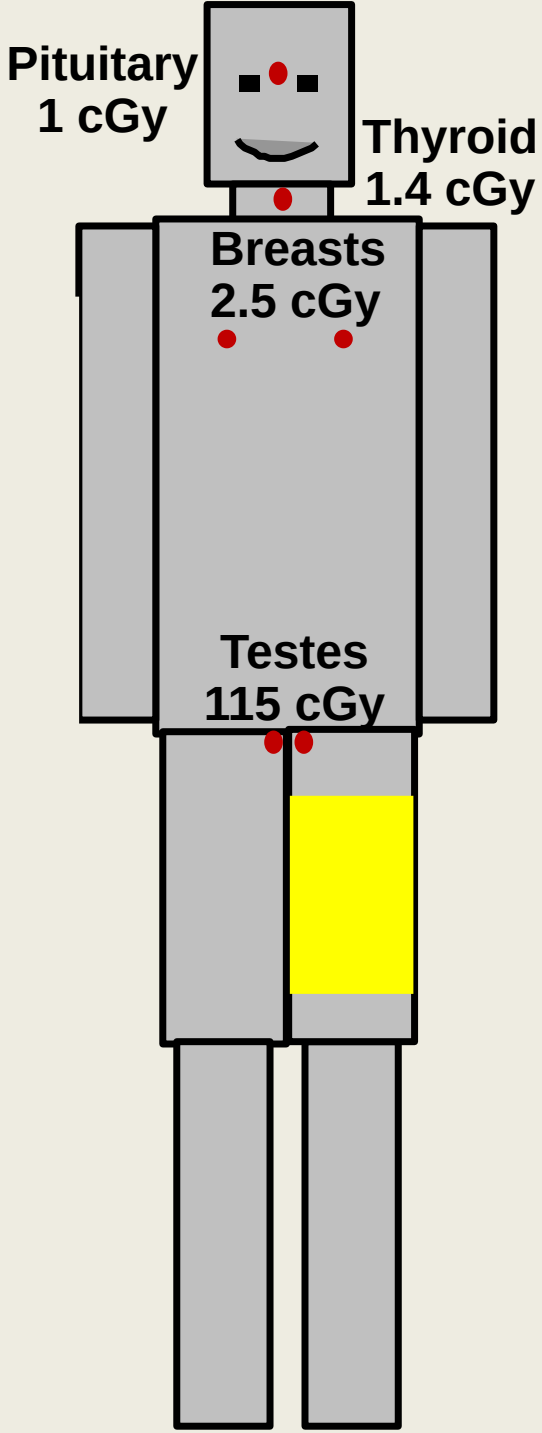
- Field can be placed in any position.
- Field geometry can be varied
- Dose calculated to point(s)
- Organs represented by a grid of points.
  - Grid can moved.
  - Grid resolution can be ⇧ or ⇩.



2.1 Mathematical Phantom Example

- **Details from RT record**
  - 16 year-old male treated for an osteosarcoma in the left thigh.
  - Field size: 12x17 cm^2
  - Field orientation: AP/PA
  - Target dose: 55 Gy
  - Beam type/energy: 6 MV photons

- Mathematical phantom + analytical model used to calculate dose to out-of-field organs.
- Often must assume location of field and relative size of patient



2.1 Variants on this process

- Particularly variants to dose model
  - Full phantom full scatter condition.
- Analytic model for breast RT
  - tangents don’t provide full scatter.
- Analytic model of skin dose from radiotherapy.
- Process is conceptually the same:
  - Abstract tx parameters of interest
  - Apply analytic model
  - Determine dose to location(s) of interest

TODAY'S TOPICS

1. Dose assessment
    1. *Treatment planning system*
    2. *Measurement*
    3. *Neutrons*
    4. *Monte Carlo*
2. Dosimetric assessment for radiation epidemiology studies
    1. *Individual dosimetry*
    2. *Reference cases*

2.2 Reference Case Approach

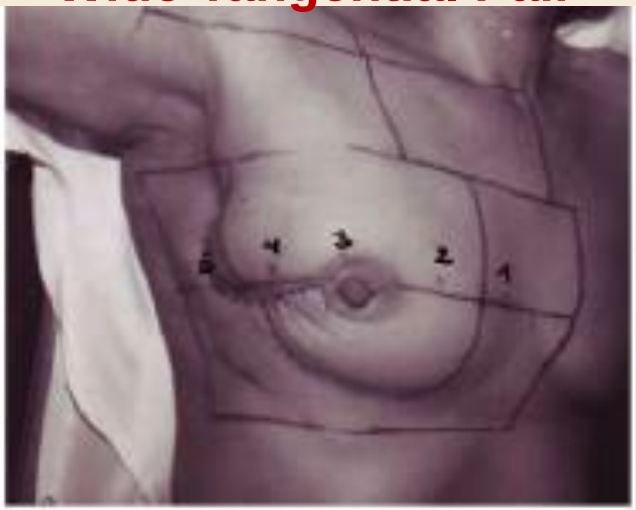
- Patients are grouped according to the nature of their treatment
  - Field orientation, modality, energy…
- Each group described by a reference treatment
- Doses are calculated for each reference treatment on a phantom (typically a single phantom).
- All patients treated according to that reference treatment are ascribed that dose.
- This approach has been used in many studies

2.2 Reference Case Dosimetry

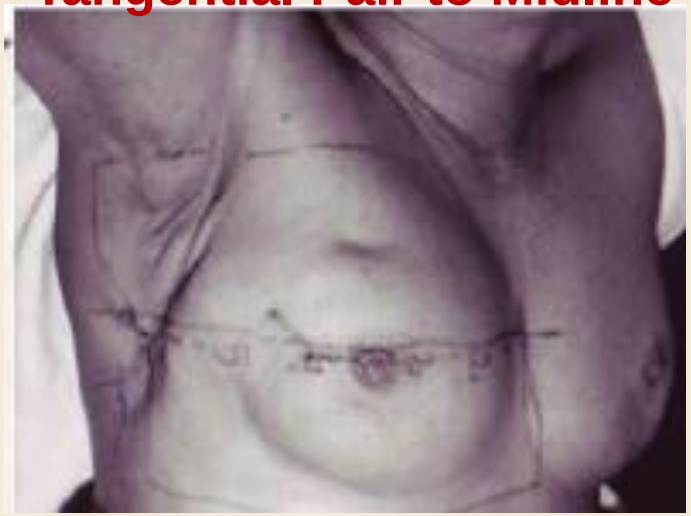
- Example study: cardiac toxicity following breast RT
- Radiotherapy treatments categorized according to regimen:
  - laterality, field arrangement, prescription dose(s), dose/fx.
- 22 standard treatment regimens.
  - Each patient was classified to a particular regimen based on data in treatment chart.

2.2 Reference treatments

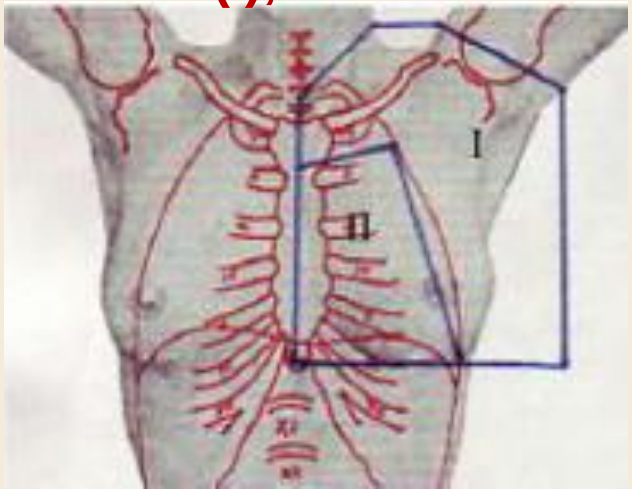
Wide Tangential Pair



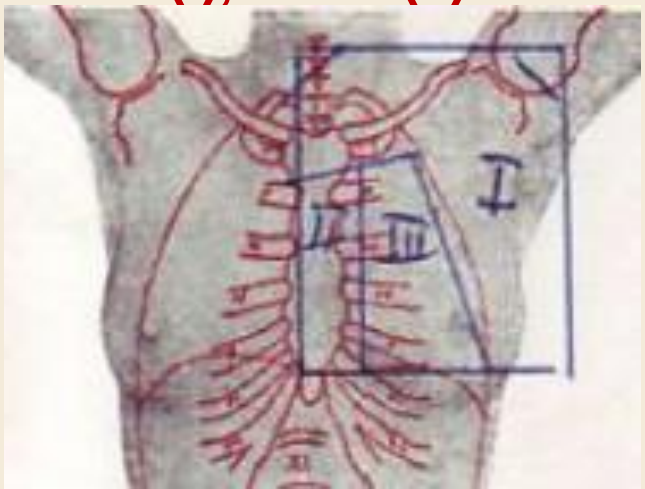
Tangential Pair to Midline



Lat thorax (I), e^{-}IMC and e^{-}CW (II)



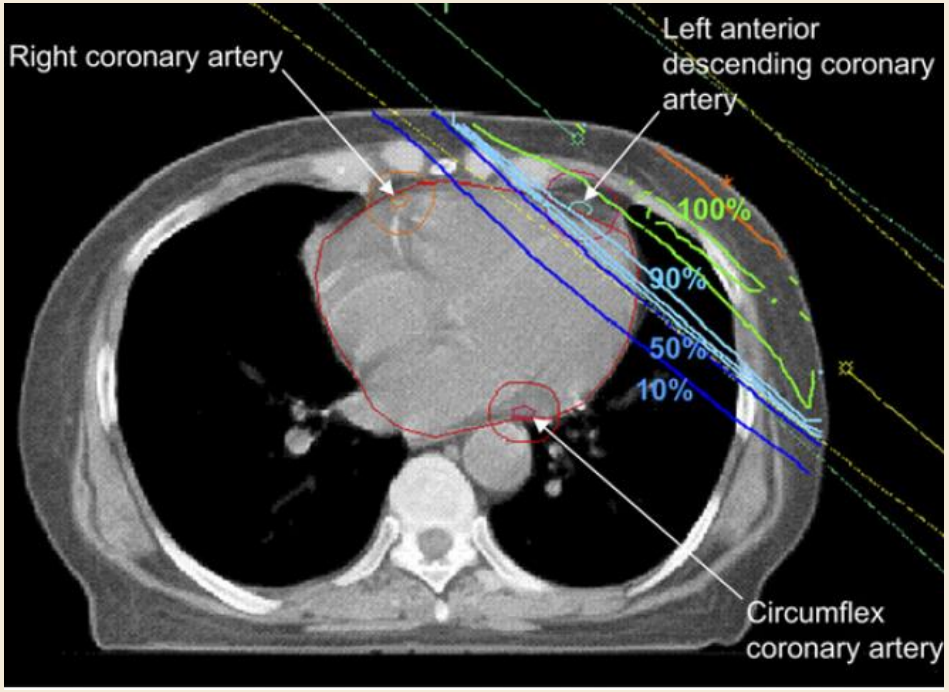
Lat thorax (I), e^{-}IMC (II) and e^{-}CW (III)



Taylor *et al.*
RO 2011

2.2 Reference dose recalculation

- The different RT regimes were reconstructed on a CT scan of typical patient of average build.
  - Heart and Coronary arteries were contoured
  - DVH were used to determine mean heart dose for each regime.
  - Heart doses were "assigned" to all patients with that regimen classification



Taylor *et al.* IJORBP 2007

TPS doesn't work for stray radiation doses!
Could apply an analytic model to determine these doses

2. Dosimetry for epidemiology summary

- Both systems struggle to define field edge
  - Charts typically don't define it well
- Both systems rely on "average" patient size and typical patient anatomy
- Both systems suffer from incomplete patient records

- Individual dosimetry better captures differences between patients
- Reference case approach better manages dosimetry within the reference case (and may be the only option if limited chart information is available)
- These differences are likely small compared to the larger uncertainty items above

Final thoughts

- Assessing the dose outside the treatment field has challenges at the best of times
- Retrospective radio-epi studies are NOT the best of times
  - Incomplete information
- The better prospective planning we can do, the better the dosimetric data we will generate.
  - Invest in the future to ensure quality data
  - Particularly as treatments become more complex

End

Thanks

- Marilyn Stovall PhD
- Rebecca Howell PhD
- Jessie Huang PhD
- Sarah Scarboro PhD
- Kiley Pulliam
- Susan Smith
- Rita Weathers

- Darby SC, Ewertz M, McGale P, et al. Risk of Ischemic Heart Disease in Women after Radiotherapy for Breast Cancer. New Engl J Med 2013;368:987-98.
- McGale P, Darby SC, Hall P, et al. Incidence of heart disease in 35,000 women treated with radiotherapy for breast cancer in Denmark and Sweden. Radiother Oncol 2011;100:167-75.
- Taylor CW, Bronnum D, Darby SC, et al. Cardiac dose estimates from Danish and Swedish breast cancer radiotherapy during 1977-2001. Radiother Oncol 2011;100:176-83.
- Taylor CW, McGale P, Povall JM, et al. Estimating Cardiac Exposure from Breast Cancer Radiotherapy in Clinical Practice. Int J Radiat Oncol 2009;73:1061-8.
- Taylor CW, Nisbet A, Mcgale P, Darby SC. Cardiac exposures in breast cancer radiotherapy: 1950s-1990s. Int J Radiat Oncol 2007;69:1484-95.
- Taylor CW, Nisbet A, McGale P, et al. Cardiac doses from Swedish breast cancer radiotherapy since the 1950s. Radiother Oncol 2009;90:127-35.