Measurement of Secondary Radiation for Electron and Proton Accelerators

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Introduction

- Patients undergoing radiation therapy are exposed to secondary radiation (radiation out of the treatment field).
- Secondary radiation is composed of photons, and at high treatment energies (above 8 MV), neutrons, which are produced in the accelerator head.

Introduction - Photons

- Secondary photon radiation composed of scatter and leakage.
- Scatter from within patient and off of collimators is dominant source near the treatment field.
- Leakage through the accelerator head is the dominant source away from the treatment field.

Introduction - Neutrons

- Neutrons are produced primarily by photons striking the primary collimator, jaws, and target.
- Neutrons are important because of their high RBE.

Radiation Type	Energy	Quality Factor
X and gamma Rays	All	1
Neutrons	< 10 keV	5
	10 keV to 100 keV	10
	100 keV to 2 MeV	20
	2 MeV to 20 MeV	10
	> 20 MeV	5

Introduction - Neutron Distribution in Treatment Room

- Primary neutrons - No energy degradation
  - Highest energy
  - Minimal relevance
- Direct neutrons - Penetrated accelerator head
  - High energy
  - Fluence decreases with distance in a semi inverse square manner
- Scattered neutrons - Scattered from objects in room and walls
  - Intermediate energy
  - Constant fluence in treatment room
- Thermal neutrons - Thermalized in walls
  - Low energy
  - Constant fluence in treatment room

Why all this Concern?

- Amount of secondary radiation is a function of the amount of beam-on time.
- Some IMRT treatments may require up to 4 times as many MU's to deliver as conventional treatments.
- For deep treatment sites, low energy treatments typically require more MU's than high energy treatments.
- **Bottom Line**: More MU's mean more secondary radiation.

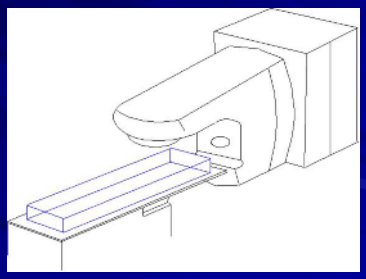
This is what started it ALL

	Likelihood of Secondary Fatal Malignancy (%)		
Technique	6 MV	18 MV	25 MV
Conventional	0.3	1.8	3
MLC modulated	1.0	5.1	8.4
Serial Tomotherapy	2.7	14.9	24.4

Calculated Risk estimates Followill et al (1997)

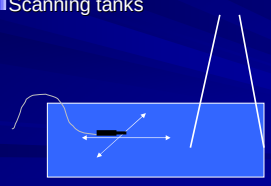
Where are we Concerned?

- Secondary radiation in the "**Patient Plane**"!!



Let's First Worry about Photons

- Early measurements – early 80's
  - Ion chambers in large water phantoms
    - Large volume ion chambers (0.3 – 30 cc)
    - Scanning tanks



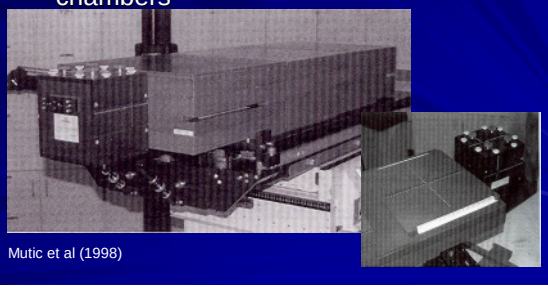
More Measurements

- Phantoms began to more closely approximate actual patient geometry
  - Using cylindrical ion chambers

From TG36 report (1993)

More Measurements

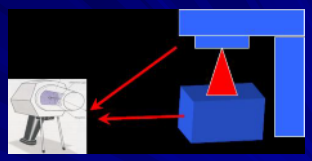
- Solid geometric phantoms also used
  - Using TLD, diodes and 0.6 cm^3 ion chambers



Mutic et al (1998)

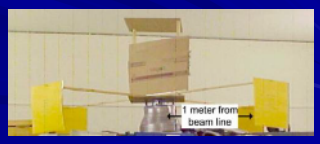
Unique Measurements

- Use of a survey meter in air



Dong et al (2000)

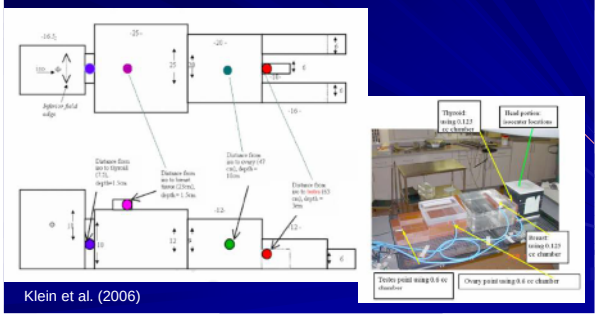
- Use of film to measure leakage



Balog et al (2005)

More Measurements

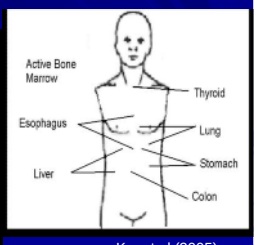
- Solid geometric phantoms also used
  - Using cylindrical small volume ion chambers



Klein et al. (2006)

Most Recent Measurements

- Anthropomorphic Rando phantom with TLD at 10 specific organ sites.
- 3 TLD at each location.



Kry et al (2005)

Photon Dosimeters

- Photon and neutron dose equivalents determined independently.
  - Li:F TLD used to measure photon dose.
    - TLD-100 used at 6 MV.
    - TLD-700 used at all other energies.
  - Neutron fluence measured with gold foils.

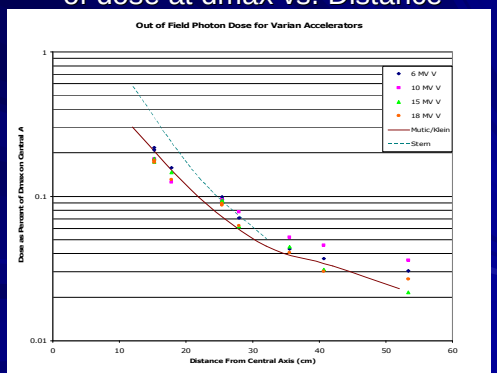
Photon Measurement Cautions

1. Biggest issue: low doses = very low rdgs.
   - Increase in uncertainty of measurements
   - Long exposure times
2. Need for multiple rdgs. at each point.
3. Rdg. location (air vs. phantom) or at what depth?
4. Point vs. volume measurements.
5. Neutron component for high X-ray energies

Photon Dose Equivalent per MU

Organ Site	Photon Dose Equivalent per MU (μSv)						
	18 MV C	6 MV V	6 MV S	10 MV V	15 MV V	15 MV S	18 MV V
Colon	39.6	19.0	18.5	15.5	15.0	17.1	16.0
Liver edge	31.1	18.3	18.5	15.6	15.8	16.9	15.6
Stomach edge	29.3	13.7	14.4	10.7	12.7	13.4	11.7
Liver center	15.8	8.2	8.9	8.1	7.9	9.1	8.1
Stomach center	14.6	8.2	8.6	7.9	8.0	8.5	7.8
Esophagus edge	16.2	8.6	8.9	7.9	8.1	8.6	7.9
Lung edge	9.6	6.1	7.8	6.7	5.3	7.7	5.6
Lung center	5.9	3.7	5.9	4.4	3.8	6.5	3.6
Esophagus center	4.1	3.2	5.6	3.9	2.6	4.8	2.7
Thyroid	2.6	2.6	6.0	3.0	1.8	5.1	2.3
Bone Marrow	16.9	9.2	10.3	8.4	8.1	9.8	8.1

Photon Dose Equivalent as a percent of dose at dmax vs. Distance



Neutron Measurements

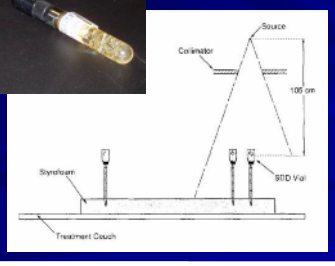
- Determining neutron dose equiv. composed of several steps
  - Obtain NIST traceable calibration
  - Measure neutron fluence
  - Calculate neutron dose equivalent at d_{max}
  - Calculate neutron dose equivalent at depth

Neutron Measurements

- Neutron fluence measured with gold foils.
  - $^{197}Au(n,\gamma)^{198}Au$
- Count the γ,β emissions of the foils, convert to neutron fluence by NIST traceable conversion factor: 3516000 n/cm^2/cps/g
- Gold foils detect thermal neutrons.
  - Bare gold foils measured the thermal neutron fluence. Bare foil hung in room center.
  - Fast neutrons are thermalized by moderators. Gold foils placed in moderators thereby measure the fast neutron fluence. Moderators were placed on central axis, at 30 cm superior, 60 cm superior, and 30 cm inferior.

Neutron Measurements

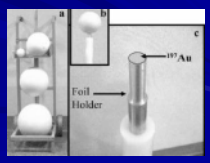
- Bubble detectors or neutron meters



Neutron Measurements

- Bonner sphere system to measure the neutron spectrum from which the fluence is deconvolved.

Howell et al (2006)

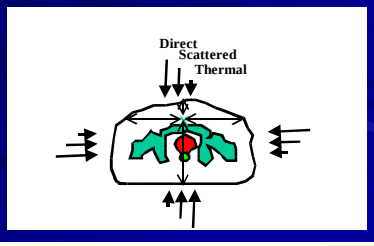


Neutron Fluence

- Fast neutron fluence measured on CAX and out of field.
- Fast neutron fluence out of field varied by less than the uncertainty in the dosimeter. Fast neutron fluence assumed constant out of field.
- Neutron fluence was examined at the same 10 points as where the photon dose was measured.

Neutron Fluence

- For each distance from central axis (each measurement point), the neutron fluence is broken down into 12 components to account for energy and geometry.
- The neutron dose equivalent at d_{max} was propagated to neutron dose equivalent at depth of measurement point



Neutron Measurement Cautions

1. Gold foil activation – not for everyone.
   - NIST traceability
   - Still the “gold” standard
2. Biggest issue: low doses = very low rdgs.
   - Increase in uncertainty of measurements
   - Long exposure times
3. Need for multiple rdgs. Along patient plane.

Neutron Dose Equivalent per MU

Organ Site	Neutron Dose Equivalent per MU (μSv)				
	18 MV C	10 MV V	15 MV V	15 MV S	18 MV V
Colon	9.8	0.11	4.6	2.5	12.0
Liver edge	12.3	0.17	6.0	3.3	15.0
Stomach edge	11.1	0.15	5.4	3.0	13.6
Liver center	9.0	0.09	4.2	2.3	11.0
Stomach center	9.1	0.09	4.2	2.4	11.1
Esophagus edge	7.4	0.06	3.3	1.9	9.1
Lung edge	11.8	0.16	5.7	3.2	14.4
Lung center	7.1	0.06	3.2	1.8	8.7
Esophagus center	5.7	0.05	2.5	1.4	7.0
Thyroid	10.4	0.20	5.2	2.9	12.7
Bone Marrow	16.8	0.28	9.0	4.7	18.6

% Neutron Contribution

Organ Site	Percent of Total Dose Equivalent from Neutrons				
	18 MV C	10 MV V	15 MV V	15 MV S	18 MV V
Colon	20	0.7	23	13	43
Liver edge	28	1.1	28	16	49
Stomach edge	28	1.3	30	18	54
Liver center	36	1.1	35	21	58
Stomach center	38	1.2	35	22	59
Esophagus edge	31	0.7	29	18	54
Lung edge	55	2.3	52	29	72
Lung center	55	1.3	46	22	71
Esophagus center	58	1.2	49	23	72
Thyroid	80	6.1	74	36	85
Bone Marrow	50	3.3	53	32	70

Neutron Trend

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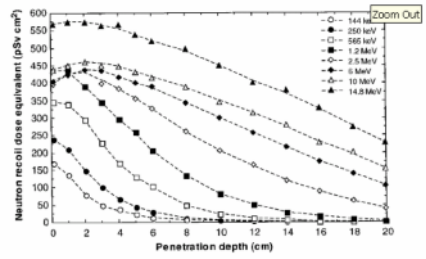
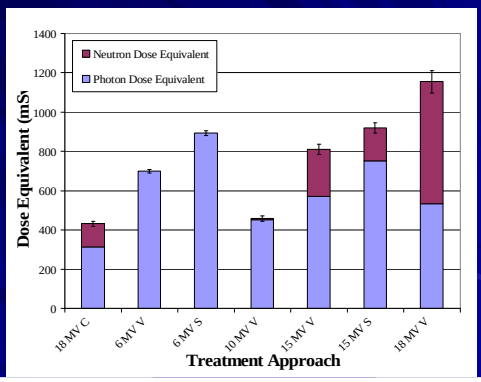


Fig. 6. Monte Carlo estimates of depth dose equivalent from neutron recoils (according to ICRP 60) for unit fluence of monoenergetic neutrons impinging on a slab-phantom.

Dose Equivalent to Edge of Stomach



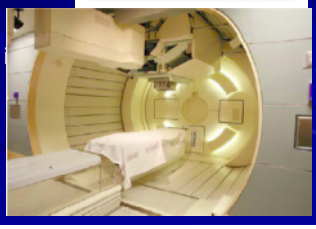
Ranking of Treatments

Organ Site	Rank of Treatment Approach						
	18 MV C	6 MV V	6 MV S	10 MV V	15 MV V	15 MV S	18 MV V
Colon	1	4	6	2	3	5	7
Liver close	1	3	6	2	4	5	7
Stomach close	1	3	5	2	4	6	7
Liver center	1	3	5	2	4	6	7
Stomach center	1	3	4	2	5	6	7
Esophagus close	1	3	5	2	4	6	7
Lung close	1	3	4	2	5	6	7
Lung center	1	2	5	3	4	6	7
Esophagus center	1	2	5	3	4	6	7
Thyroid	3	1	5	2	4	6	7
Bone Marrow	1	3	4	2	5	6	7
Average	1.2	2.7	4.9	2.2	4.2	5.8	7.0

– 1=Lowest dose equiv., 7=Highest dose equiv.

What about Proton Facilities?

- Currently 27 facilities in 11 countries treating patients
- 12 additional facilities in the planning stage or under construction in 8 countries
- Within a few years there will 7 facilities the USA



Is there any Secondary Radiation to worry about?

YES!

Proton beams generate neutrons by interacting with the scattering systems, range modulator wheel, collimators and even the patient

Neutron Measurements

Investigator	Proton Delivery	Detector	Dose Range (mSv/Gy) @ 50 cm
Yan et al.	Pass. Scattering	Bonner Sphere (LiI)	**2.5**
Binns et al.	Pass. Scattering	TE Prop. Counter	**59**
Roy et al.	Pass. Scattering	Bubble Detector	**0.10**
Schneider et al.	Pencil beam	Bonner Sphere	**0.07**
Polf et al.	Pass. Scattering	Monte Carlo Calculation	**1.5**

Mapping of the Neutron Dose Equivalent

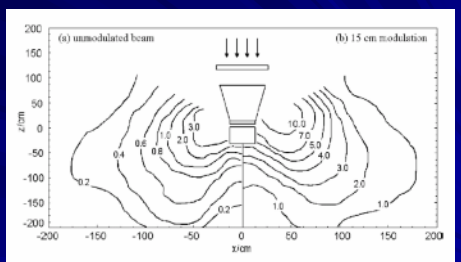


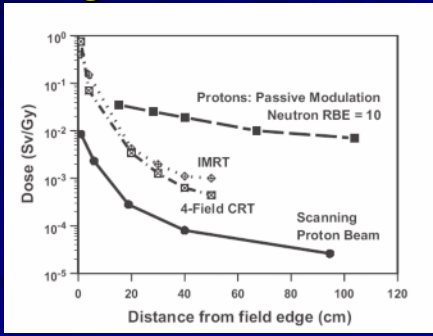
Figure 7. Isodose contour plot of the calculated total neutron dose equivalent per absorbed dose $(H/D)^{\mathrm{nt}}_{\mathrm{tot}}$, in units of mSv Gy^{-1}, for an unmodulated beam (a) and a 15 cm SOBP (b).

Polf et al. (2005)

Neutron Measurements

- Data is sparse – 4 sets of measurements
- Results are not consistent
- Measurement techniques are not consistent
- Many different factors affect neutron production
  - Proton energy
  - Range modulation
  - Field size
  - Lateral scattering technique

How significant can this be?



Hall (2006)

Neutron Measurement Cautions

1. Neutron energies much higher than observed around electron accelerators
2. Is your neutron calibration technique calibrated appropriately for these "neutrons"?
3. Very long exposure times
4. Moderators and foils used on electron accelerators are not adequate.

Summary

- There is an increased secondary dose from IMRT.
  - The increase depends on the number of MUs and the photon beam energy.
- Measurement of the secondary dose requires an established NIST traceable technique – both photons and neutrons.
- Proton beams produce secondary neutron doses.
- No consensus as to the best measurement technique – more work needed.