

Radiation Protection: Are We Doing Enough To Protect Our Patients and Staff ?

Wayne Newhauser, Ph. D.



Univiversity Texas M. D. Anderson Cancer Center
Proton Therapy Course, 2008-05-21, Jacksonville

Acknowledgments

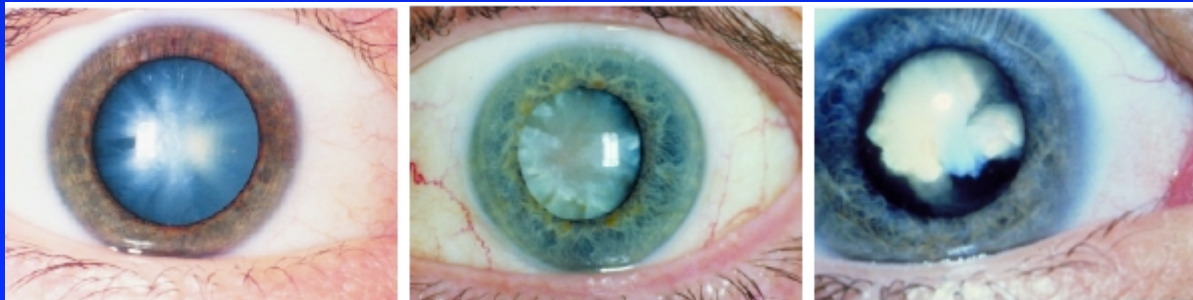
- PTCOG organizers and sponsors
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Objectives of Lecture

- Review the basics of radiation protection
 - Guiding principles
 - Practical Methods
- Example 1: Shielding of a proton center
- Example 2: Protecting patients from stray radiation
- Try to answer, “Are we doing enough?”

Review: Deterministic Effects

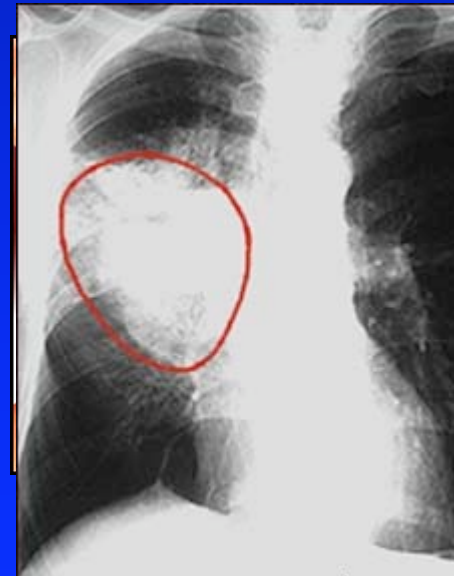
- **Severity increases with dose**, above a threshold
- Effect usually occurs after large doses
- Occurs hours, days, months or years after exposure
- Examples
 - Reduction in fertility
 - Cataracts



National Eye Institute

Review: Stochastic Effects

- Probability increases with dose
- Severity independent of dose (**all or nothing**)
- Principal effect after exposure to low doses
- Examples
 - **Lung Cancer**
 - Genetic effects

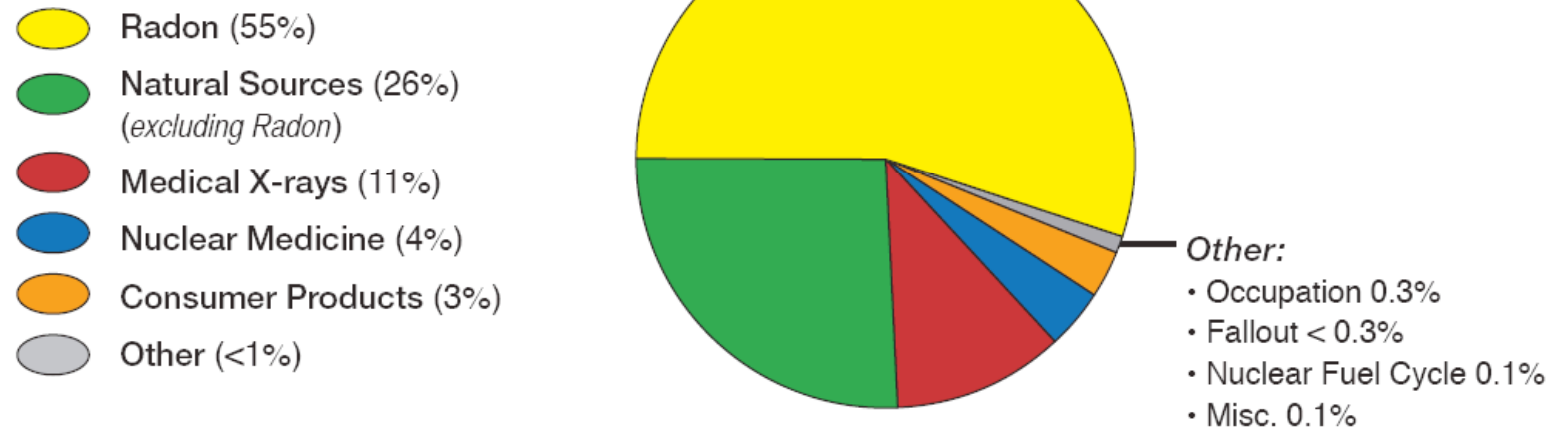


www.nlm.nih.gov

Review: Average Radiation Exposure

Sources of Radiation Exposure

From: NCRP Report No. 93



Natural background ~82% (from BEIR VII 2006)

Total is about 3.6 mSv/y (360 mrem/y) from NCRP 93.

Principles of Radiation Protection:

Goals

- Prevent occurrence of serious radiation-induced conditions in exposed persons. These include acute and chronic **deterministic** effects.
- Reduce **stochastic** effects in exposed persons to a degree that is acceptable in relation to the benefits to the individual and society from the activities that generate such exposure.

After NCRP Report 116, 1993

Goal: Radiation Should be a Safe Industry.

Risk of Fatal Ca Should $\sim 10^{-4}/\text{y}$ or less

TABLE 3.1 — *Fatal accident rates in various industries, 1976 and 1991.*

	Mean rate 1976 ^a (10^{-4} y^{-1})	Mean rate 1991 ^b (10^{-4} y^{-1})
All groups	1.42	0.90
Trade	0.64	0.40
Manufacture	0.89	0.40
Service	0.86	0.40
Government	1.11	0.90
Transport and public utilities	3.13	2.20
Construction	5.68	3.10
Mines and quarries	6.25	4.30
Agriculture (1973-80)	5.41	4.40

^aReference NSC (1977).

^bReference NSC (1992).

From NCRP Report 116, 1993

Principles of Radiation Protection: Approach

- To **prevent the occurrence** of clinically significant radiation induced *deterministic* effects by adhering to dose limits that are below the apparent threshold levels.
- To **limit the risk** of *stochastic* effects, cancer and genetic effects, to a *reasonable* level in relation to societal needs, values, benefits gained and economic factors.

After NCRP Report 116, 1993

Principals of Radiation Protection: Practical Methods

- Radiation safety training
- Time, distance, **shielding**
- Administrative controls on use, occupancy
- Interlocks, annunciators, and other safety systems
- Radiation survey measurements
- Area monitoring of radiation levels
- Personal dosimetry, **personal risk assessment**
- Oversight by radiation safety committee
- As low as reasonably achievable (ALARA)

Methods: Formalism to Compute Risk

- Effective dose
 - Sums over all tissues and organs (T)
 - w_T is the tissue weighting factor

$$E = \sum_T H_T \cdot w_T$$

- Equivalent dose
 - Sums over all radiation (R) types
 - w_R is the radiation weighting factor

$$H_T = \sum_R w_R \cdot D_T$$

Where Do w_R and w_T Come From?

- An end user should use *recommended* values
 - Regulatory compliance, see **state regulations**.
 - Research, see **advisory bodies** (ICRP, NCRP, BEIR).
- Values were derived mainly from studies of **survivors of the atomic bomb**, and occupational and medical exposures.

Tissue Weighting Factors

Tissue or organ	Tissue weighting factor, 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
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05 ^{2,3}

From ICRP Publication 60 (1990)

Radiation Weighting Factors

Table 1. A comparison of existing w_R values and those proposed to the ICRP

Type and energy range of incident radiation	Radiation weighting factor (w_R)	
	<i>Publication 60</i>	Proposed ^c
Photons, all energies	1	1
Electrons and muons (all energies) ^a	1	1
Protons (incident)	5	2
Neutrons, energy < 10 keV	5	Use the proposed w_R function in Fig. 1 below
10 keV–100 keV	10	
> 100 keV–2 MeV	20	
> 2 MeV–20 MeV	10	
> 20 MeV	5	
Alpha particles, fission fragments, and heavy ions ^b	20	20 ^d

^a Exclude Auger electrons from emitters localising to cell nucleus/DNA- special treatment needed.

^b Use Q-LET relationships of *Publication 60* for unspecified particles.

^c Changes for neutron energies < 1 MeV are required to account for gamma contribution to internal organs (see text).

^d ICRP Committee 4 Task Group on Radiological Protection in Space Flight to consider w_R for high energy neutrons and heavy ions of LET > 200 keV/μm.

ICRP Publication 92 (2003)

Neutron Radiation Weighting Factor

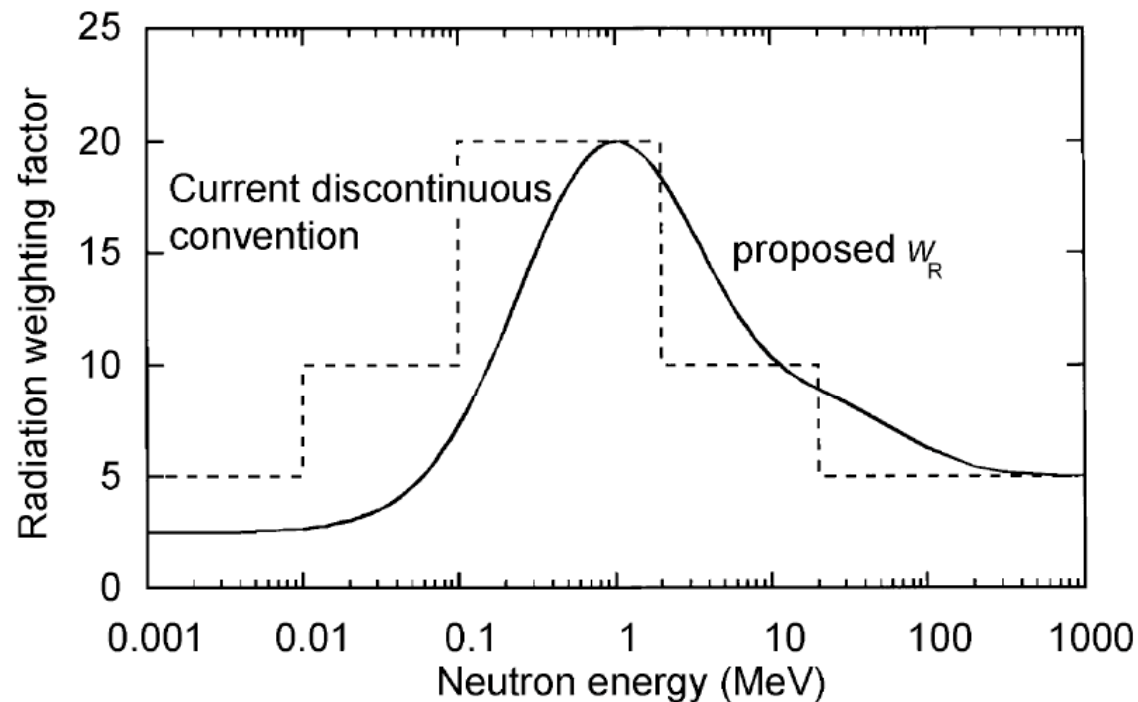


Fig. 1. The radiation weighting factor w_R for neutrons introduced in *Publication 60* (ICRP, 1991) as a discontinuous function of the neutron energy (---) and the proposed modification (—).

$$w_R = 2.5 \left[2 - e^{-4 E_n} + 6 e^{-(\ln(E_n))^2 / 4} + e^{-(\ln(E_n / 30))^2 / 2} \right]$$

ICRP Publication 92 (2003)

What Are Exposure Limits to *People*?

- Occupational exposures
 - Annual: $E < 50 \text{ mSv}$
 - Cumulative: $E_{\text{cum}} < (10 \text{ mSv}) \times (\text{age in years})$
 - Lens of eye: $< 150 \text{ mSv/y}$
 - Skin, hands, feet: $< 500 \text{ mSv/y}$
- Public (one tenth of occupational limits)
- Embryo and Fetus: $< 0.5 \text{ mSv/month}$
- Negligible Individual Dose: $< 0.01 \text{ mSv/y}$

Condensed from NCRP Report 116, 1993. *Check your local regs!*

What Are Limits in an *Area*?

- Uncontrolled Area
 - $E < 500 \text{ mSv/y}$
 - $< 0.02 \text{ mSv}$ in any one hour
- Designation of Radiation Areas
 - “Radiation Area”: $> 0.05 \text{ mSv/h}$
 - “High Radiation Area”: $> 1 \text{ mSv/h}$
 - “Very High Radiation Area”: $> 5 \text{ Sv/h}$

Condensed from NCRP Report 116, 1993

Shielding: Design Challenges

Complexity

Many sources and barriers

Radiation transport physics

Regulatory requirements

Uncertainty

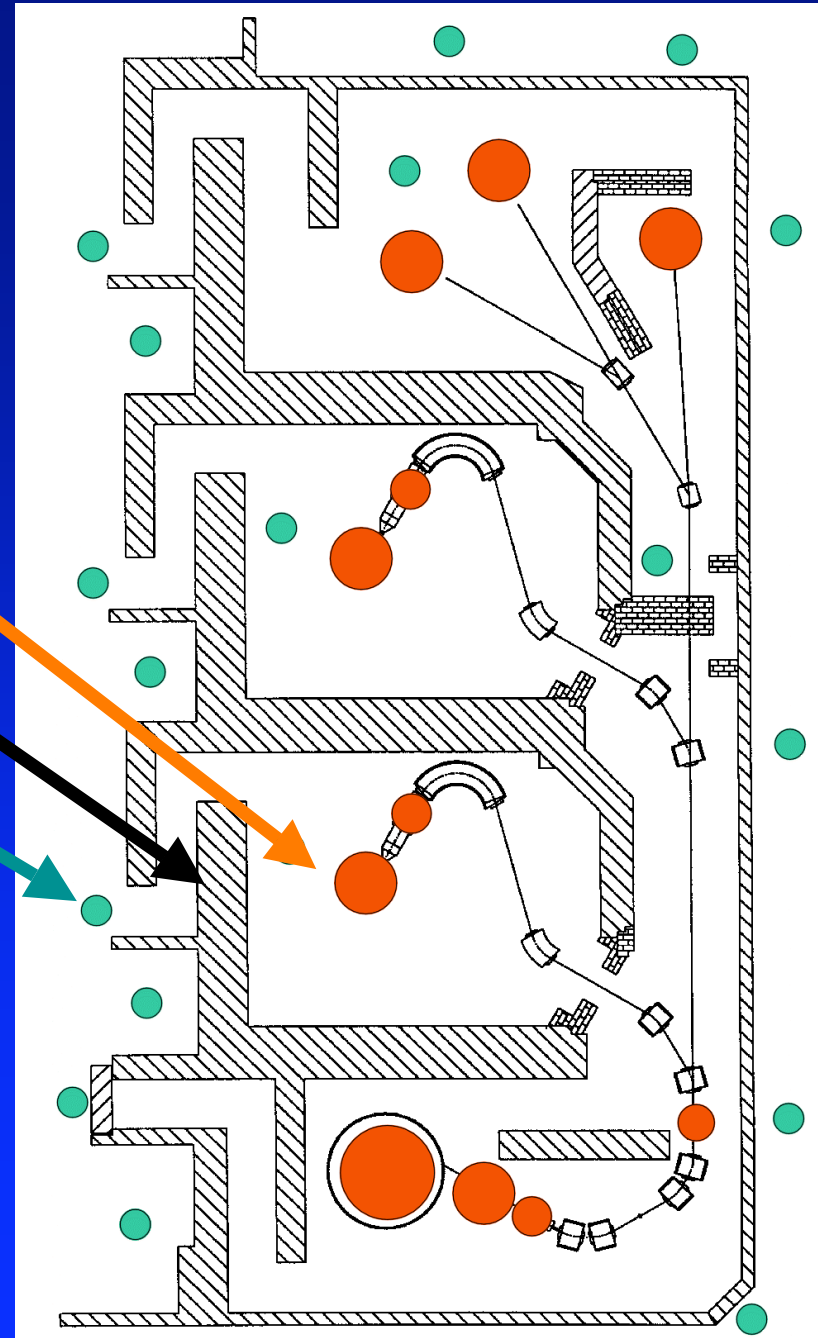
Facility usage patterns

Equipment performance

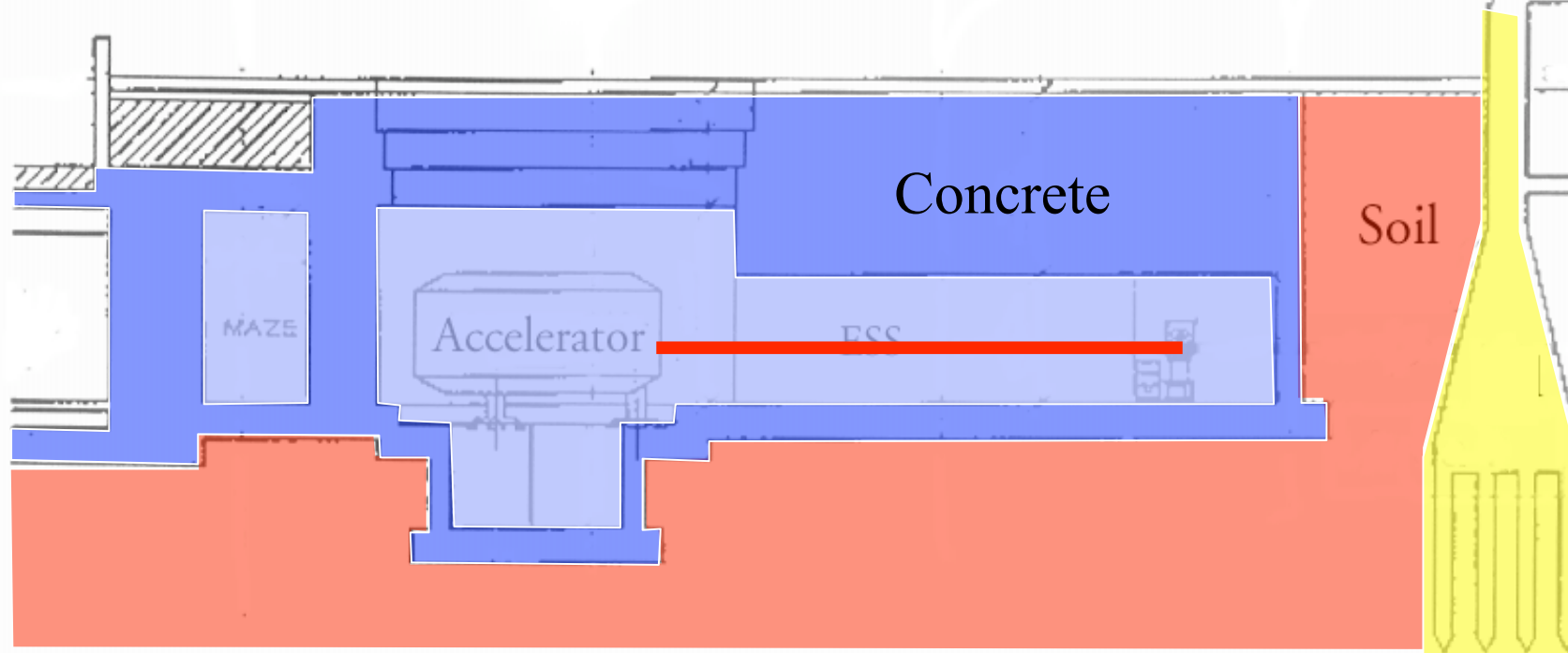
Basic data

Neutron Shielding Calculations

Neutron Source
Neutron Shield
Dose Calc Point



Shielding Materials



Newhauser *et al.* Northeast Proton Therapy Center Report Number NPTC-HD-107, 2000.

Common Design Assumptions

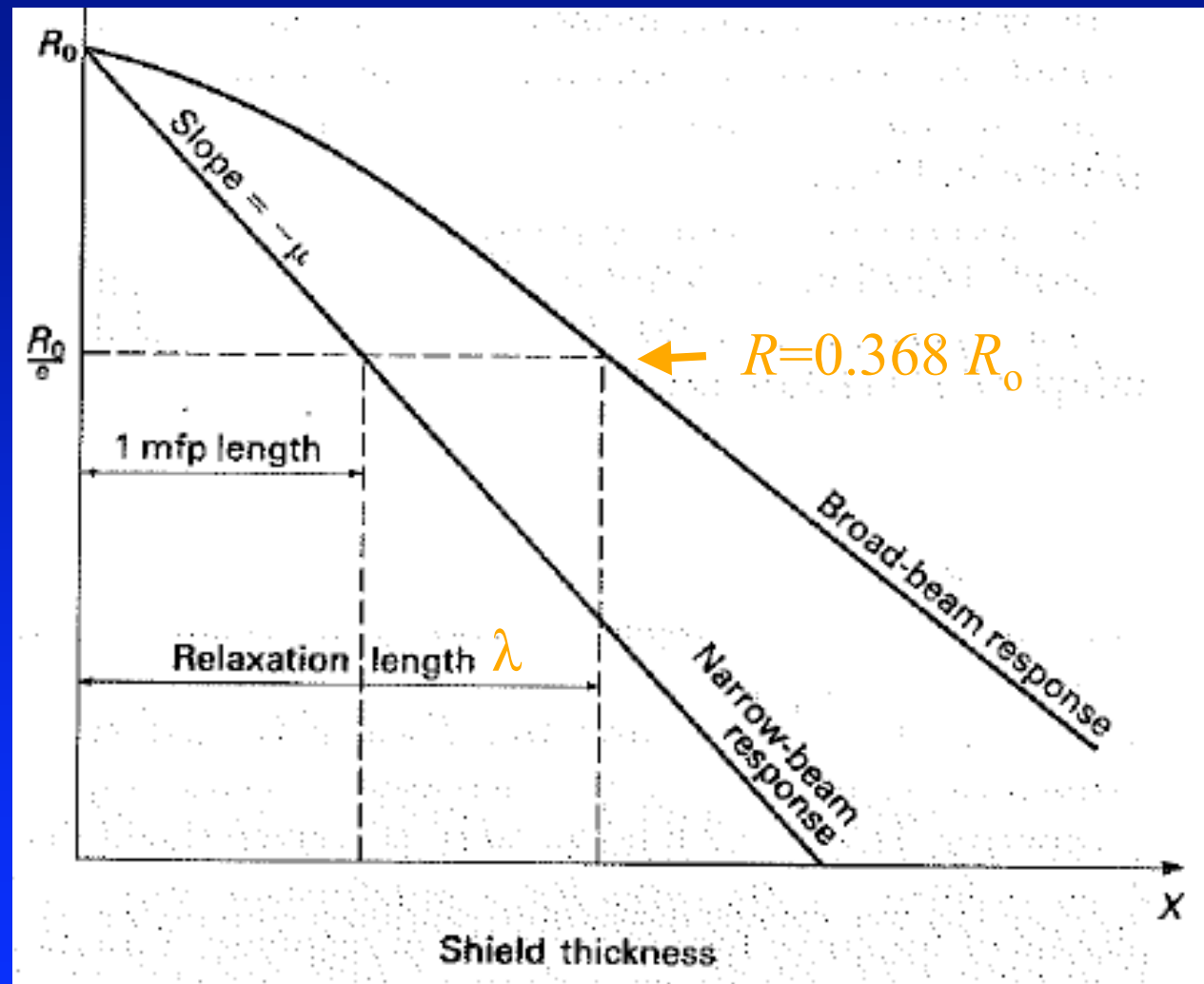
- Vault shielding is determined by **neutrons**, not by protons or photons
- Therapeutic protons should **never** be incident on the primary shielding barriers
- Workload, Use Factors, and Occupancy Factors are conceptually analogous (but numerically different) to those for linac-based photon therapy (See NCRP Report 151, 2005)

Exponential Attenuation

Attenuation length (λ)
or relaxation length

Half value layer
 $\lambda = 0.693/\text{HVL}$

Tenth value layer
 $\lambda = 2.3/\text{TVL}$



After AB Chilton, Engr Compendium Radiat Shielding, 1968

Moyer Model for Slab Shielding

SHIELDING OF PROTON ACCELERATORS: A COMPARISON BETWEEN THE MOYER MODEL AND MONTE CARLO CALCULATIONS

H. DINTER and K. TESCH

Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, FRG

C. YAMAGUCHI

KEK, National Laboratory for High Energy Physics, Oho 1-1, Tsukuba, Japan 305

Received 5 September 1988

NIM A276 (1989) 1-7

$$H(z) = H_0 \left(\frac{E}{E_0} \right)^{\alpha} e^{-\beta\theta} \frac{\exp(-d/(\lambda_H \sin \theta))}{r^2}$$

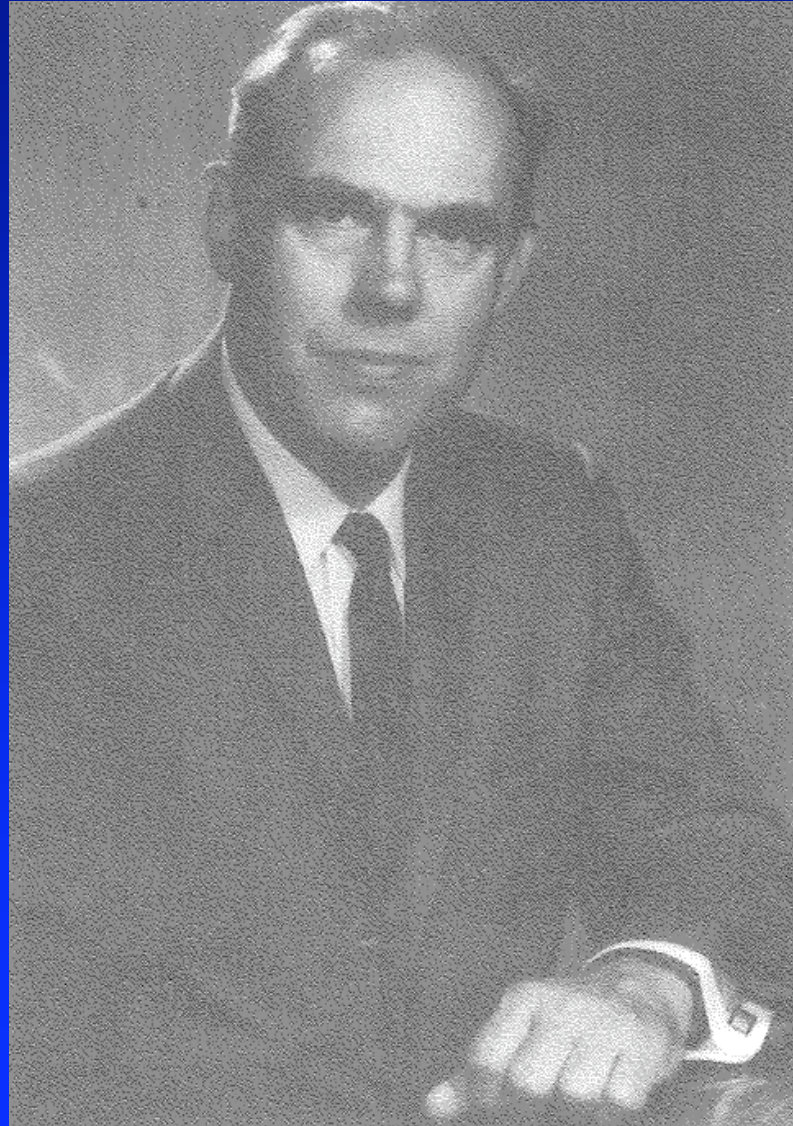
Production

Angular
Distribution

Attenuation,
Inverse Square

Burton Moyer

Father of Accelerator Health Physics



From Paterson and
Thomas, Eds., 1994

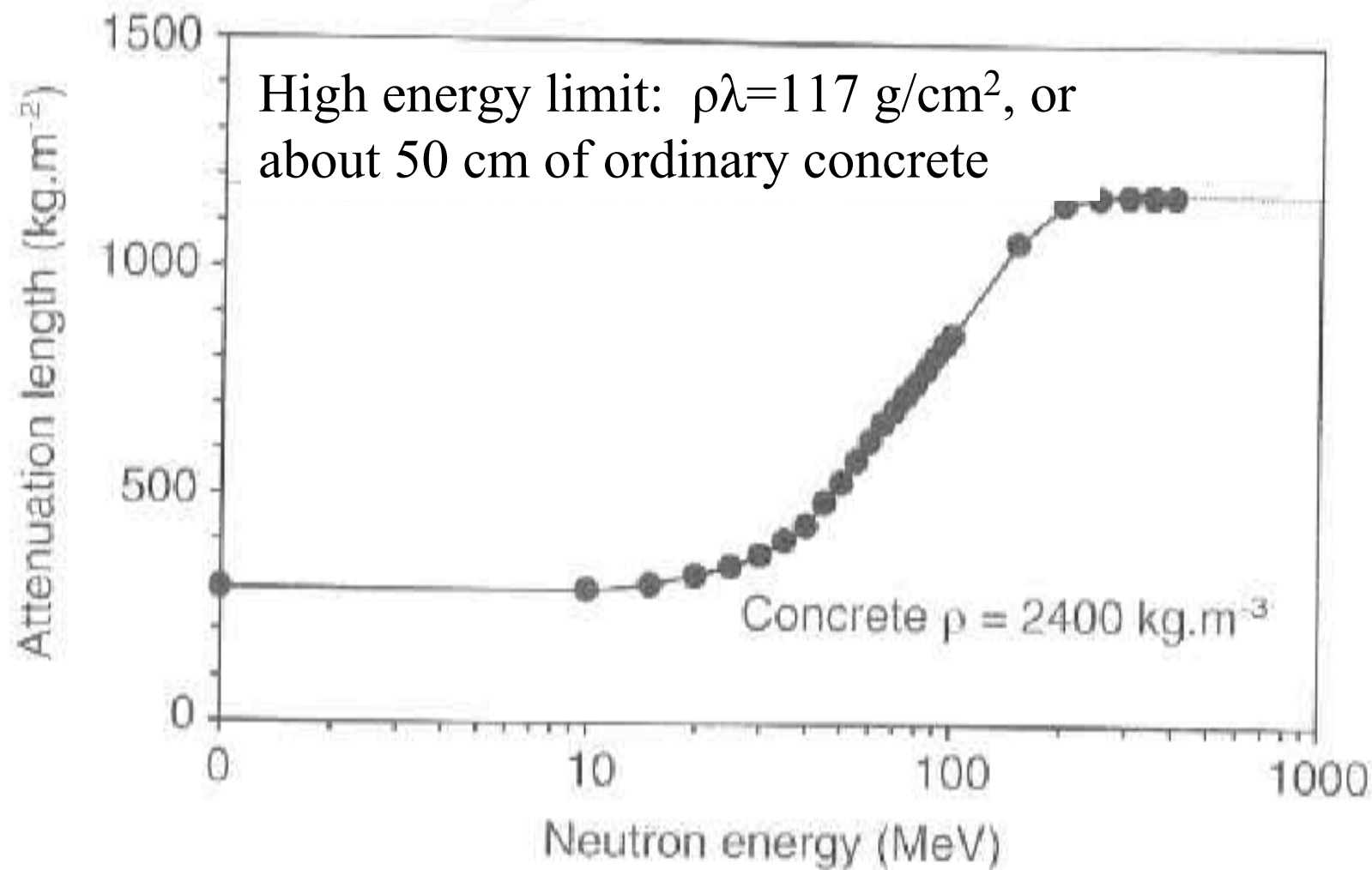
Dose Equivalent Source Terms

Table 1. Source term and attenuation length in concrete TSF-5.5 for forward and lateral shielding for neutrons produced by 250 MeV protons on thick copper, iron and tissue targets (from Ref. 42).

Angular bin	Fe		Cu		Tissue	
	H_0 per proton (Sv.m ²)	λ (g.cm ⁻²)	H_0 per proton (Sv.m ²)	λ (g.cm ⁻²)	H_0 per proton (Sv.m ²)	λ (g.cm ⁻²)
0°-10°	8.1E-15	108	7.0E-15	110	3.9E-15	95
10°-20°	6.9E-15	107	5.6E-15	108	3.6E-15	93
20°-30°	6.2E-15	101	4.7E-15	106	2.5E-15	92
30°-40°	4.0E-15	98	3.5E-15	100	1.8E-15	83
40°-50°	2.9E-15	96	2.5E-15	97	9.3E-16	80
50°-60°	2.0E-15	92	1.8E-15	91	7.1E-16	75
60°-70°	1.2E-15	85	1.1E-15	82	6.0E-16	67
70°-80°	7.6E-16	74	7.1E-16	72	5.0E-16	59
80°-90°	6.0E-16	64	5.7E-16	63	3.0E-16	52

From Silari, Radiat Prot Dosim 96 381 (2001), original data from Agosteo et al NIM B 114 70 (1996)

Neutron Attenuation In Concrete



L. Moritz, Radiat Prot Dosim 96 297 (2001)

Composition of Concrete

Builder's
Specification

Physicist's Specification

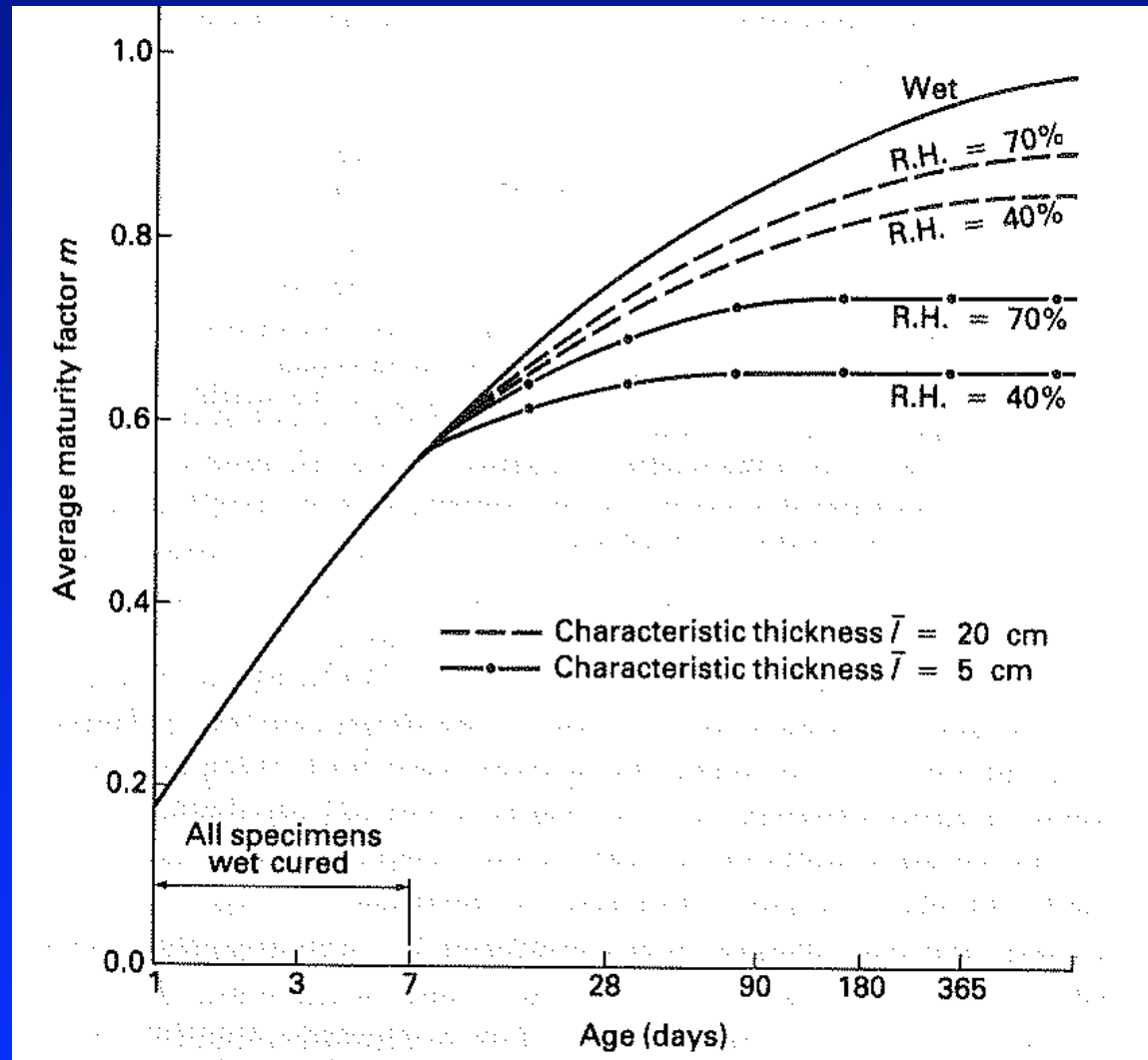
Material	Weight (%)	Volume (%)	Element	Weight (%)	Density (g cm ⁻³) ^(b)
Portland cement ^(c)	8.2	12.1	H	1.0	0.0230
Fine aggregate ^(d)	28.7	24.3	O	52.9	1.2200
Gravel	56.4	48.6	Si	33.7	0.7750
Water	6.7	15.0	Al	3.4	0.0780
			Fe	1.4	0.0320
			Ca	4.4	0.1000
			Mg	0.2	0.0050
			C	0.1	0.0023
			Na	1.6	0.0368
			K	1.3	0.0299

Especially important:
Hydrogen content
Total mass density

From M. F. Kaplan, 1989

Water Content of Concrete

- Types of Water
 - Chemically bound
 - Physically bound
 - Free flowing
- Calculations of water content are approximate



In MF Kaplan, 1989. Data from H K Hilsdorf, Nucl Engr Design, 6 251, 1967

Limitations of Moyer's Model

“The model is only an algorithm which enables experimental and theoretical data to be fitted. If one attributes physical meaning to the known parameters, inconsistencies are obtained.”

Dinter et al., NIM A276 (1989) 1

Monte Carlo to the Rescue!!!

“Hence, the Moyer model gives no insight into the physical processes which take place within the target and the shielding. **Analytical or Monte Carlo programs are required for this.**”

Dinter et al., NIM A276 (1989) 1

Fathers of the Monte Carlo Method



Stanisław Marcin Ulam in the 1950s [1].



John von Neuman in the 1940s [2].

- [1] Immediate source: <http://www.zwoje-scrolls.com/zwoje16/text03.htm> Ultimate source: Likely from Ulam's autobiography, *Adventures of a mathematician*
[2] <http://www.lanl.gov/history/atomicbomb/images/NeumannL.GIF>

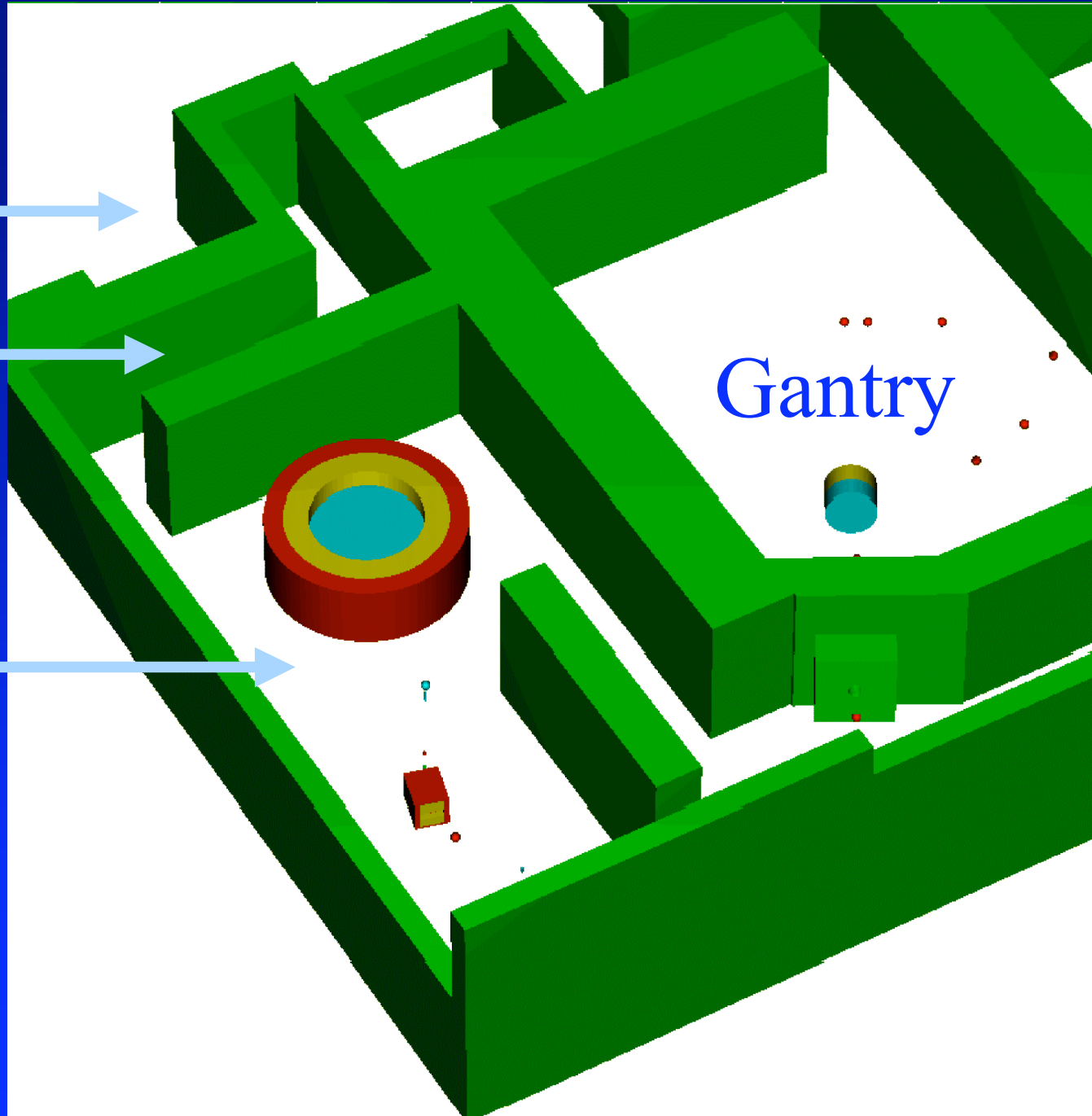
Control
Room

Maze

Cyclotron
Vault

Gantry

See Newhauser et al (2002)
and Titt et al (2005)



Comparison of Methods

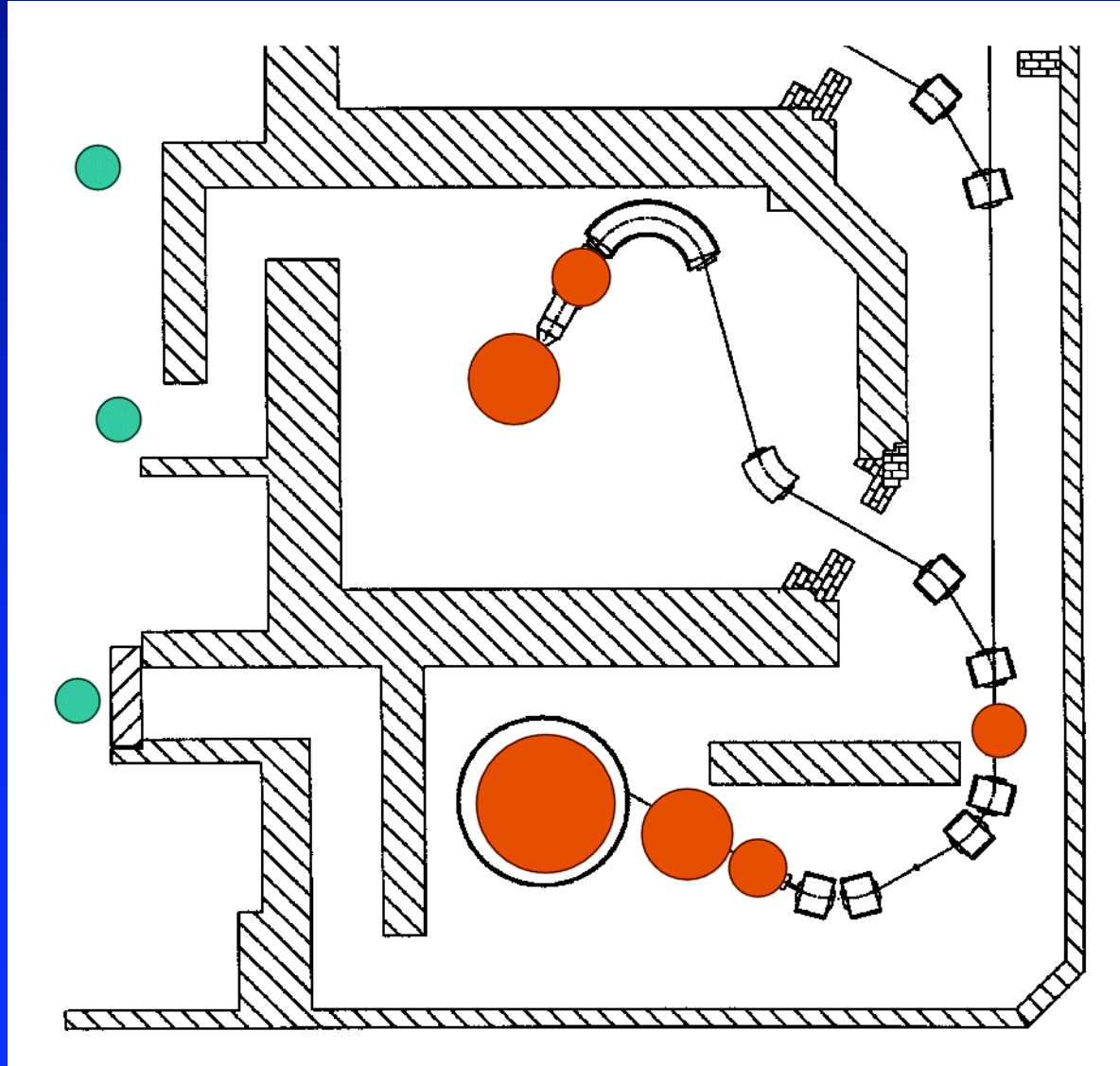
$\underline{H_a}$ $\underline{H_{MC}}$

H_m H_m

63 1.1 →

0.9 1.3 →

100 7.1 →



See Newhauser et al (2002)
and Titt et al (2005)



Now for the really hard part,

Are we doing enough to protect our *patients*?

A few different viewpoints.

Is Diagnostic Imaging a Problem?

“There may be disagreement within the medical community about the accuracy of the risk models ... These arguments will not be settled in the near term. However, one fact is indisputable: **We must continue our efforts to do a better job of reducing radiation dose to children** if and when they need a CT scan.”

Goske et al. J Roentgenology 190 273-4 (2008)

Is Radiotherapy a Problem?

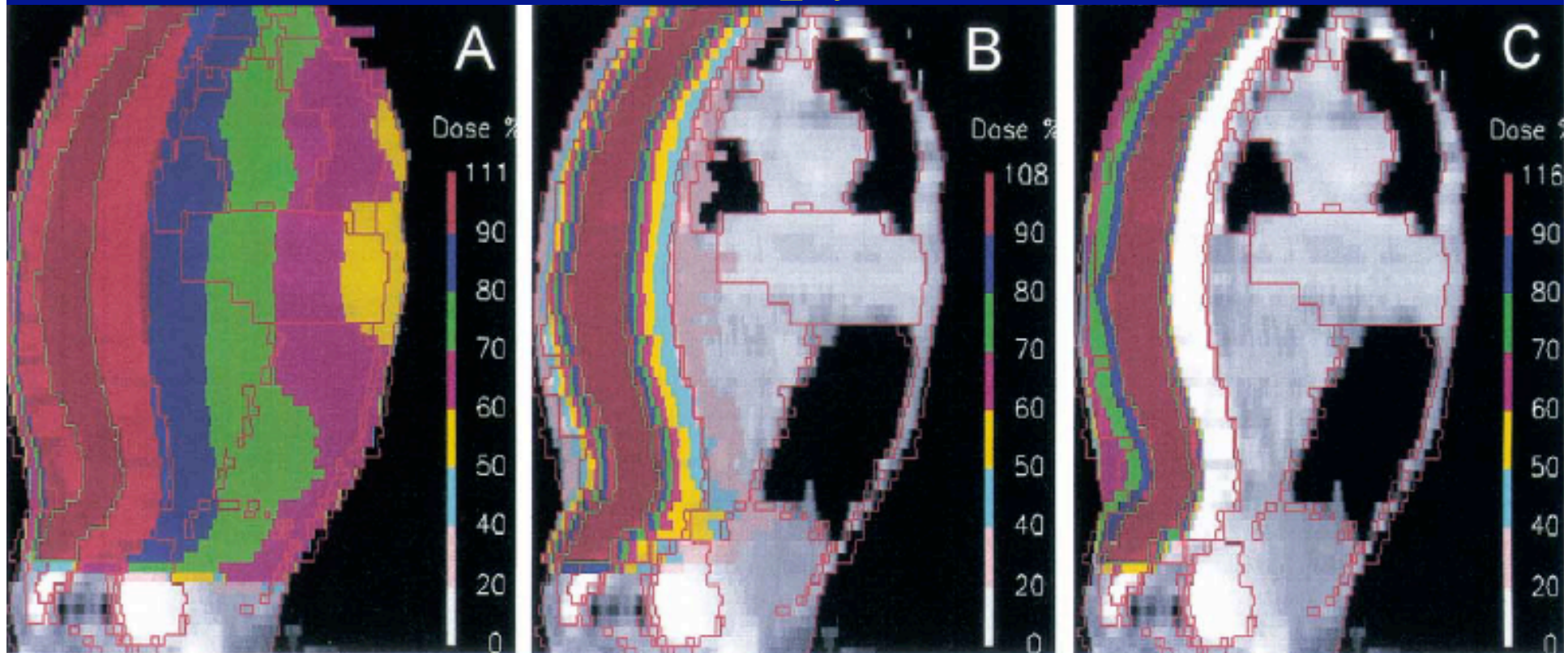
In a study published in the New England Journal of Medicine in 2006, which looked at outcomes in more than 10,000 survivors, CCSS researchers found that almost **two-thirds of patients reported at least one chronic health problem, one-quarter had a severe condition, and almost one-quarter had three or more chronic health problems. Late effects reported most frequently in this study were second cancers, cardiovascular disease, kidney disease, musculoskeletal conditions, and endocrine abnormalities.** The risk of developing a health problem related to cancer treatment in childhood increased over time.

Women face higher risks than men for late effects including breast cancer, cognitive dysfunction, heart disease, and hypothyroidism. Other factors influencing late effects include age at diagnosis, type of cancer, and types of treatment received. **Radiation treatment, especially to the brain - and, in women, the chest - carries a high risk of long-term effects.**

"Both the magnitude and the diversity of the long-term health effects have been striking," says CCSS principal investigator Dr. Les Robison of St. Jude Children's Research Hospital in Memphis. **"At 30 years after their diagnosis, more than 70 percent of childhood cancer survivors have a late-effect chronic health condition."**

From NCI Ca Bul, March 18, 2008 • Volume 5 / Number 6

Is *Photon* Therapy the Problem?



Photons
(6 MV, 1 field)
2nd ca [%/y]: 0.8
Rel. risk: 15

Photon IMRT
(15 MV, 9 field)
0.4
9

Protons
(SOBP, 1 field)
0.05
1

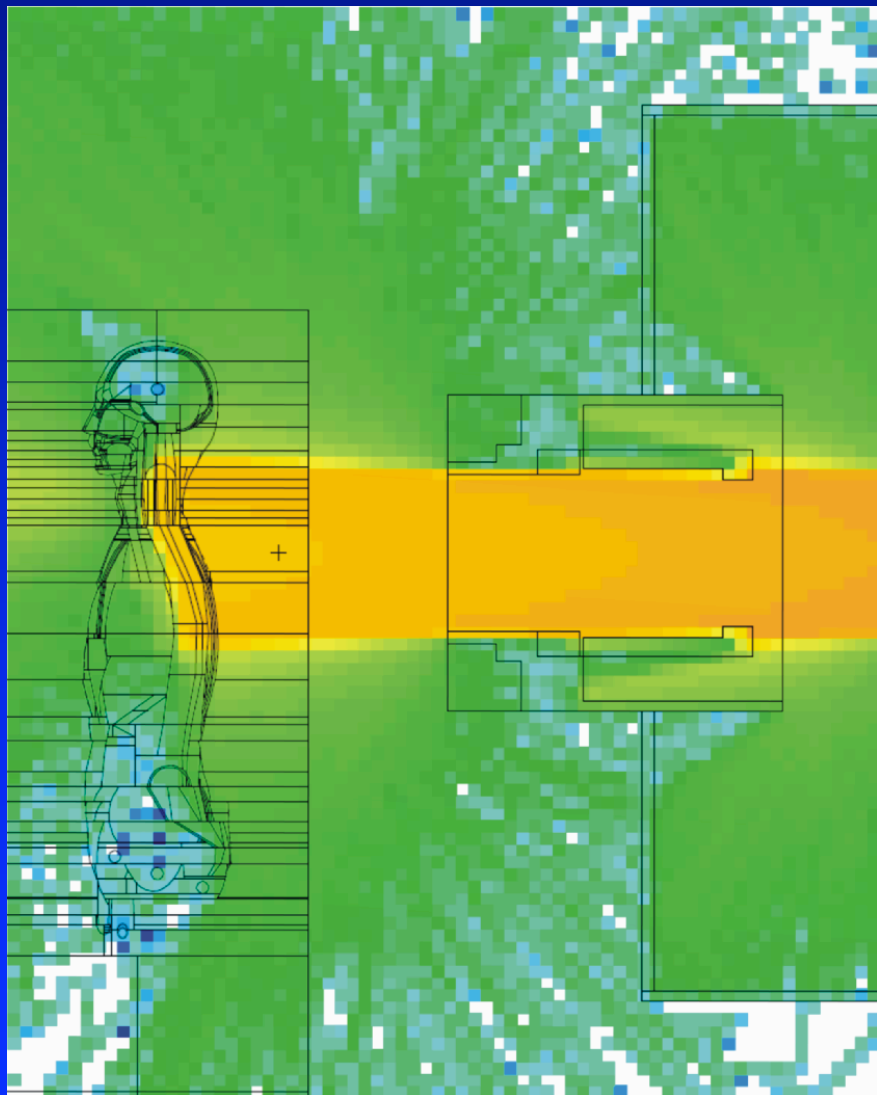
Is *Proton* Therapy the Problem?

“Does it make any sense to spend over \$100 million on a proton facility, with the aim to reduce doses to normal tissues, and then to bathe the patient with a total body dose of neutrons ...

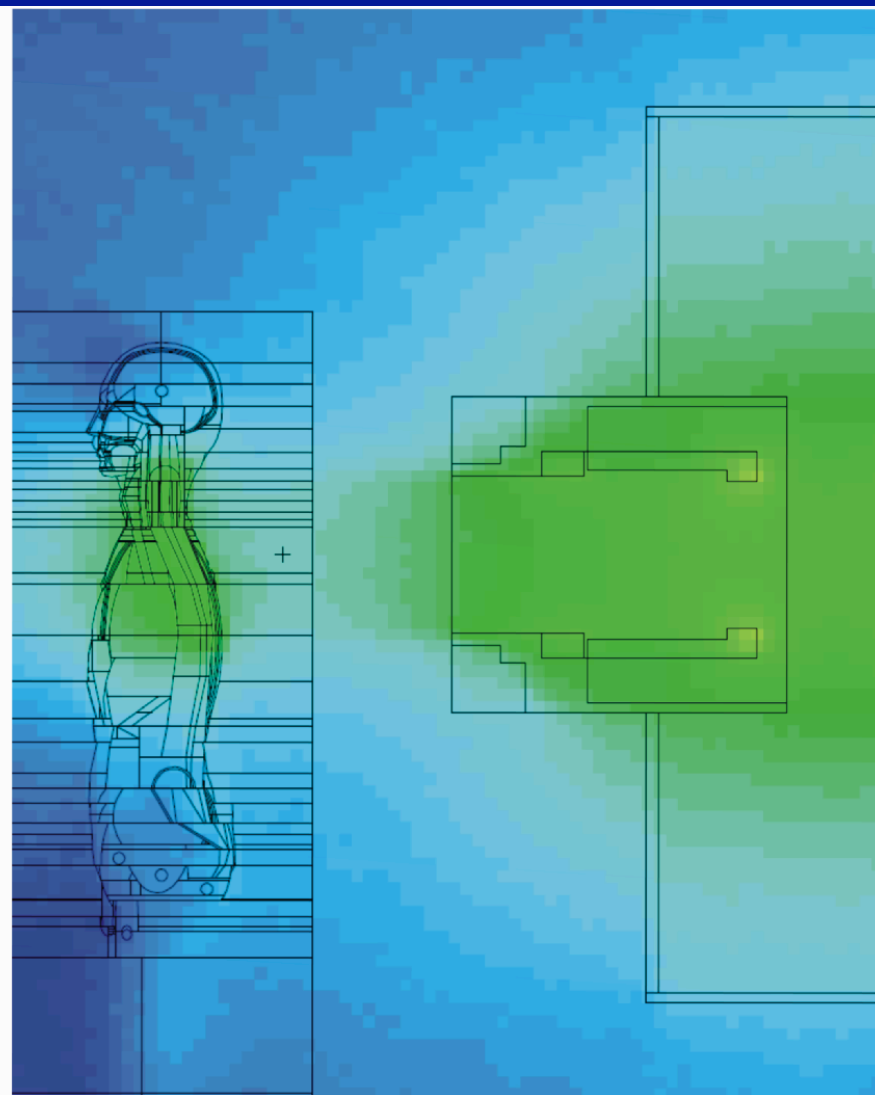
Hall, Technol in Ca Res Treat 2007;6:31-34

Are Neutrons a Problem for Children?

Logarithm of *proton* fluence (arb units)



Logarithm of *neutron* fluence (arb units)



Relative Risk of Second Cancer Including Neutrons

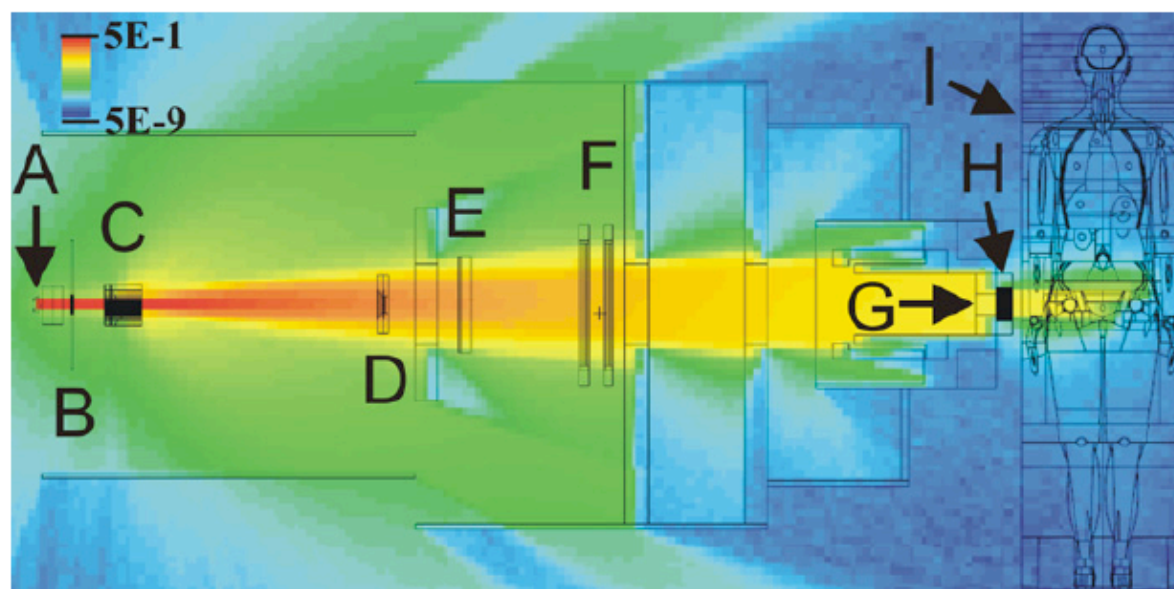
CRT	IMRT	IMPT(p)	PSPT(p+n)	Mean Q_n
15*	8.6*	1*
13	7.1	...	1	8[#]
4.4	2.5	...	1	48 ⁺

*Values from Miralbell et al., IJROBP 54 824-829 2002. Other risk values were based on data from Miralbell et al. after correcting for the risk contribution from neutrons.

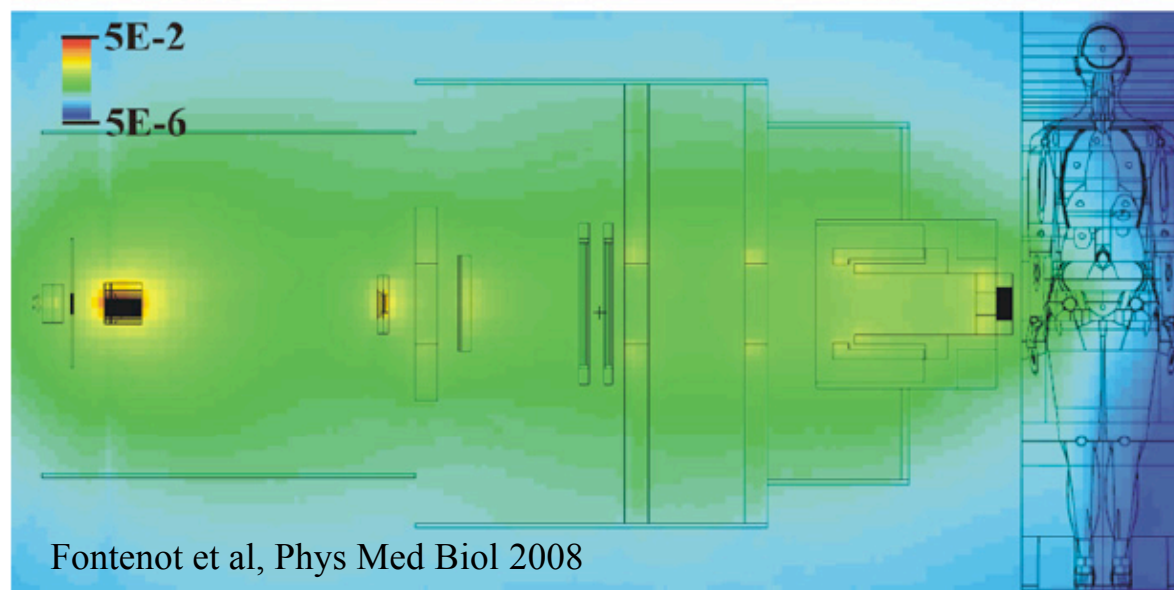
[#]Calculated using neutron spectral fluences from Monte Carlo simulations and $Q(E_n)$ data from ICRP Publication 92 (2003).

⁺Calculated as above but assuming 6x higher $Q(E_n)$ values than ICRP Pub 92.

What about protons for prostate cancer?



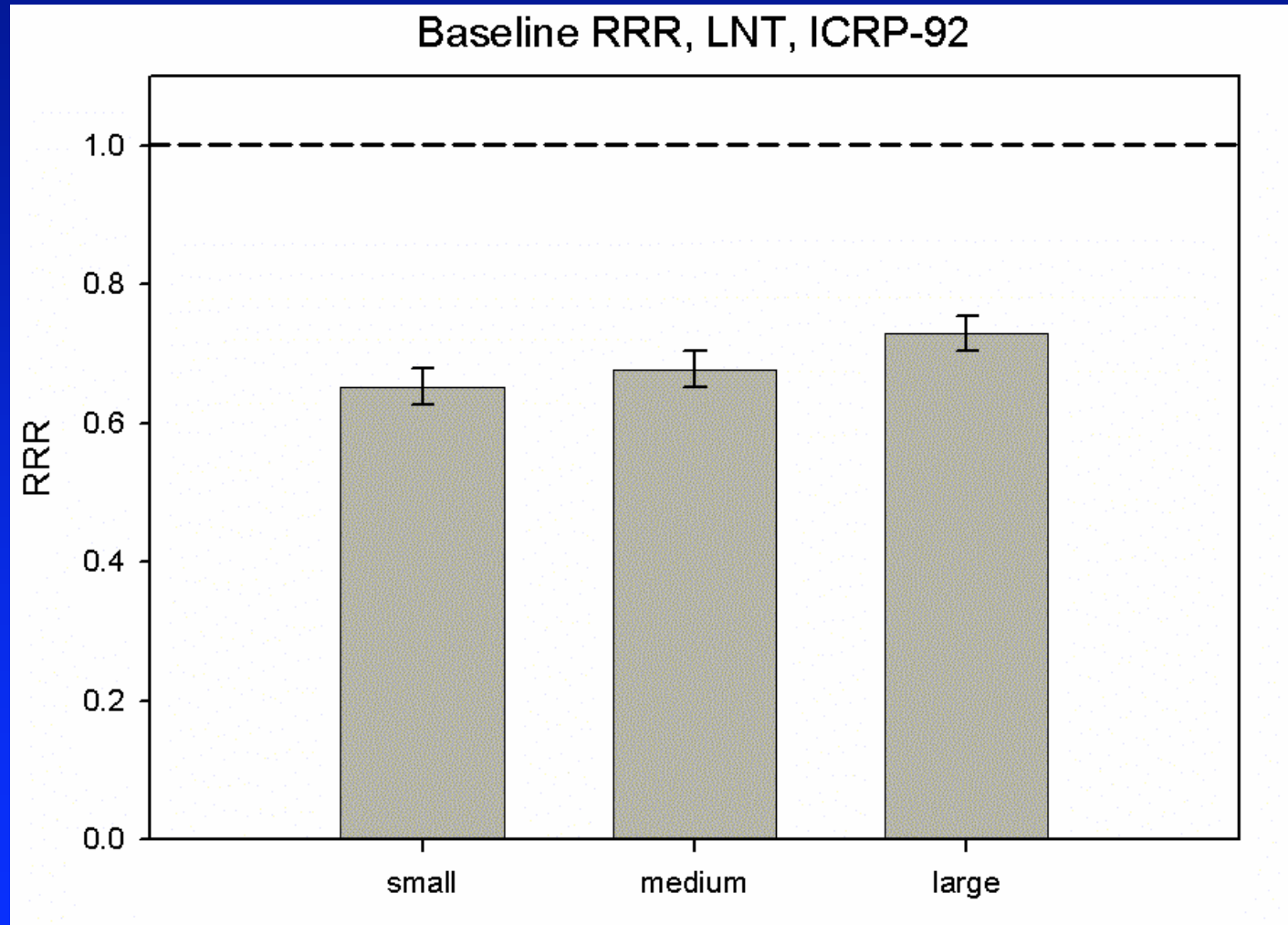
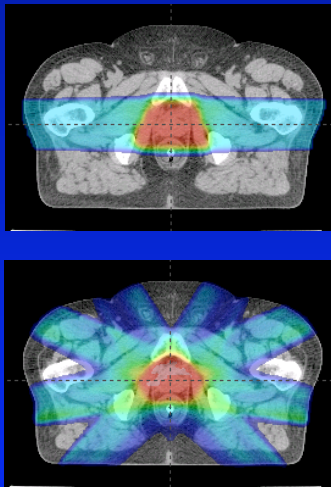
Proton fluence



Neutron fluence

Fontenot et al, Phys Med Biol 2008

Relative Risk Following PSPT vs. IMRT, including neutrons



Fontenot et al, in preparation

Is Passive Scattering a Problem?

“Protons are a major step forward for radiotherapy, but neutrons are bad news and must be minimized by the use of spot scanning techniques.”

Hall, Technol in Ca Res Treat 2007;6:31-34

Is Passive Scattering a Problem for Prostate?

- “... passively scattered proton treatment delivers an effective dose of only 415 mSv due to stray radiation. This corresponds to a **lifetime risk for developing a fatal second malignancy from stray radiation exposure of only 2%, ...**” (Fontenot et al PMB 2008)
- An optimized collimation design reduced the neutron exposures from 567 to 355 mSv, which is **only 109 mSv more than predicted for a scanned beam treatment.** (Taddei et al PMB 2008)
- Similar findings from Tayama et al (2006)

Summary

- Overview of radiation protection concepts
- Overview of shielding
- Overview of stray radiation exposures
- Are we doing enough?

End of Lecture

Protons *versus* Photons

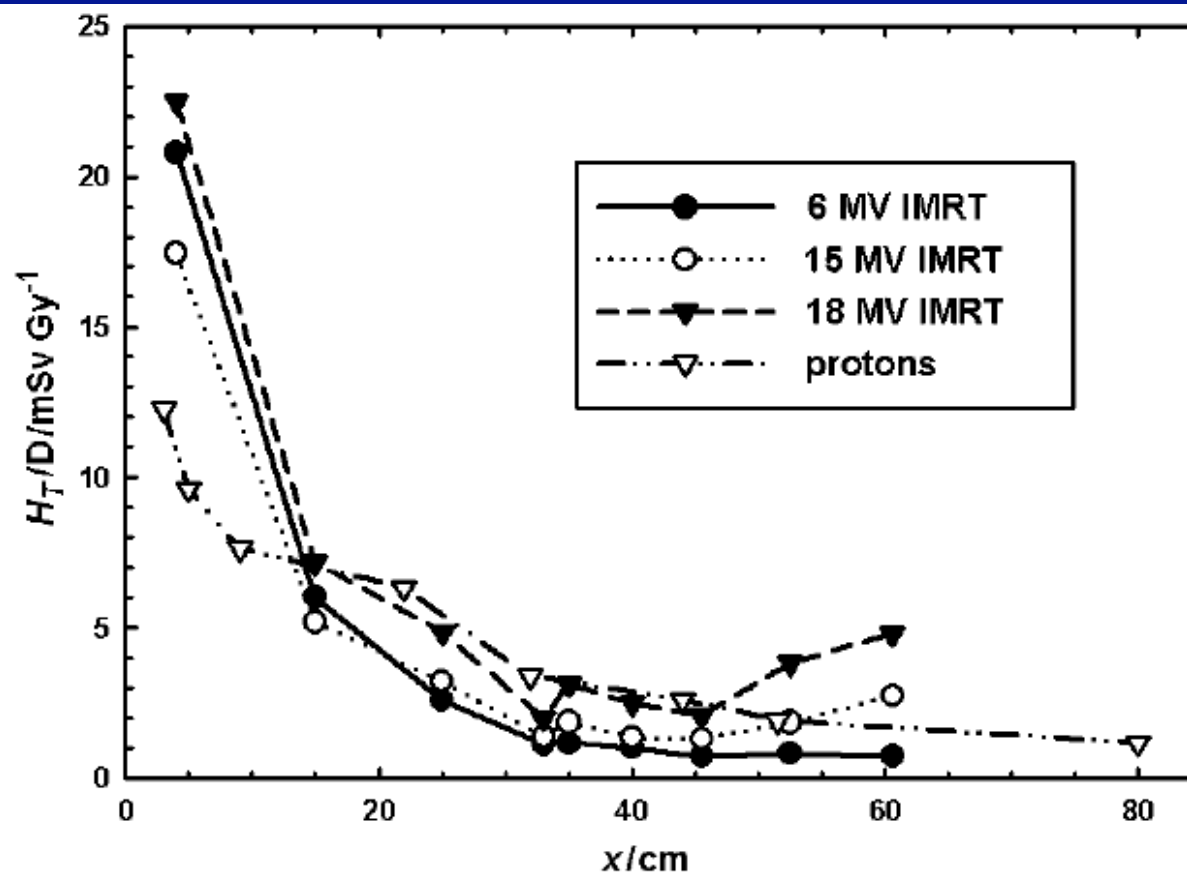
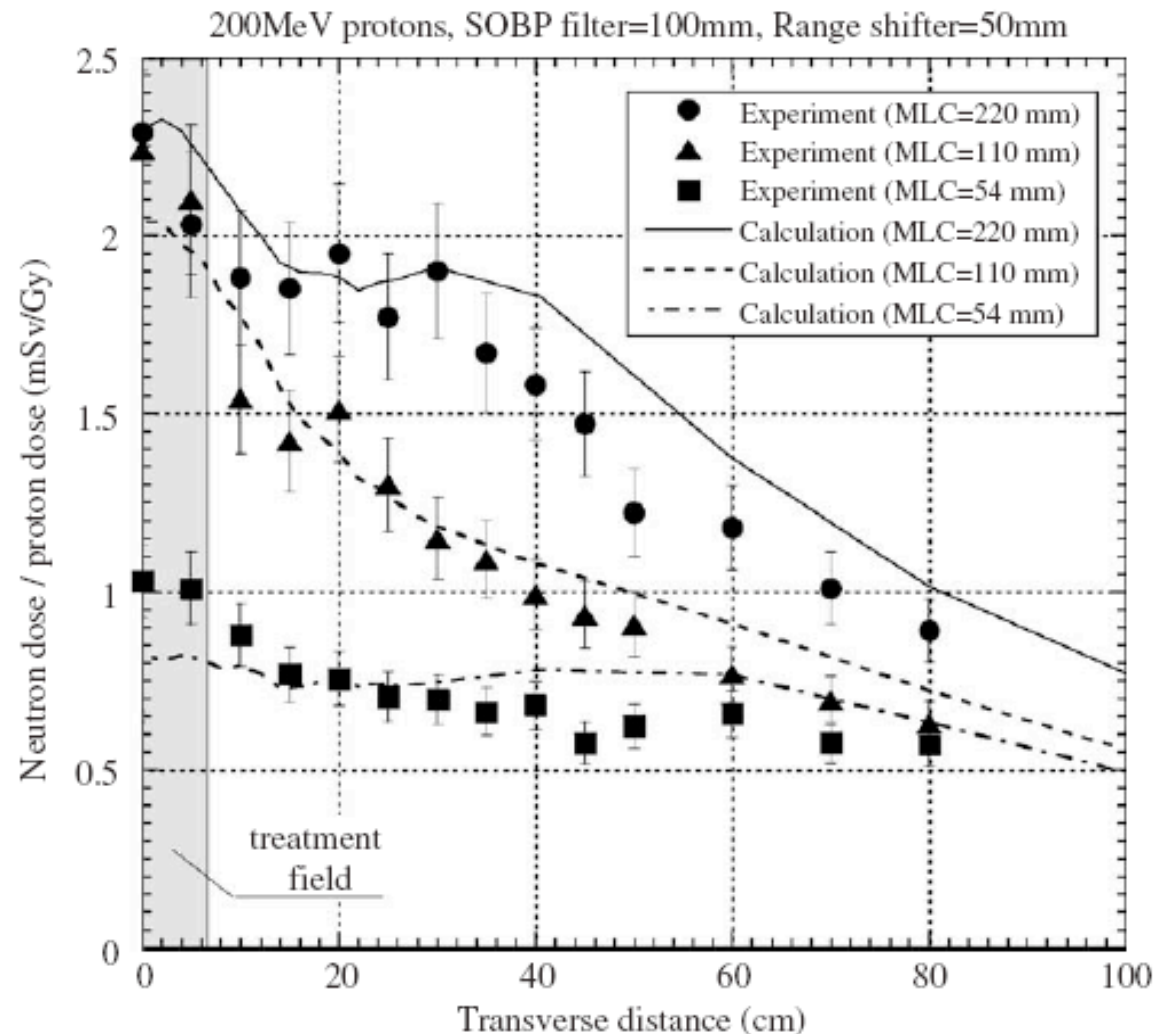


Figure 4. H_T/D as a function of lateral distance (along the patient axis) from the isocenter from this work compared to IMRT values collected from Kry *et al* (2005) and Howell *et al* (2006).

Fontenot et al, Phys Med Biol 2008

Is a lack of data and knowledge a problem?



- Yes
- Some good, e.g., Tayama et al reported MCNPX agreed within 10%.
- Some gaps, some low-quality data

Is Passive Scattering the Problem for Prostate?

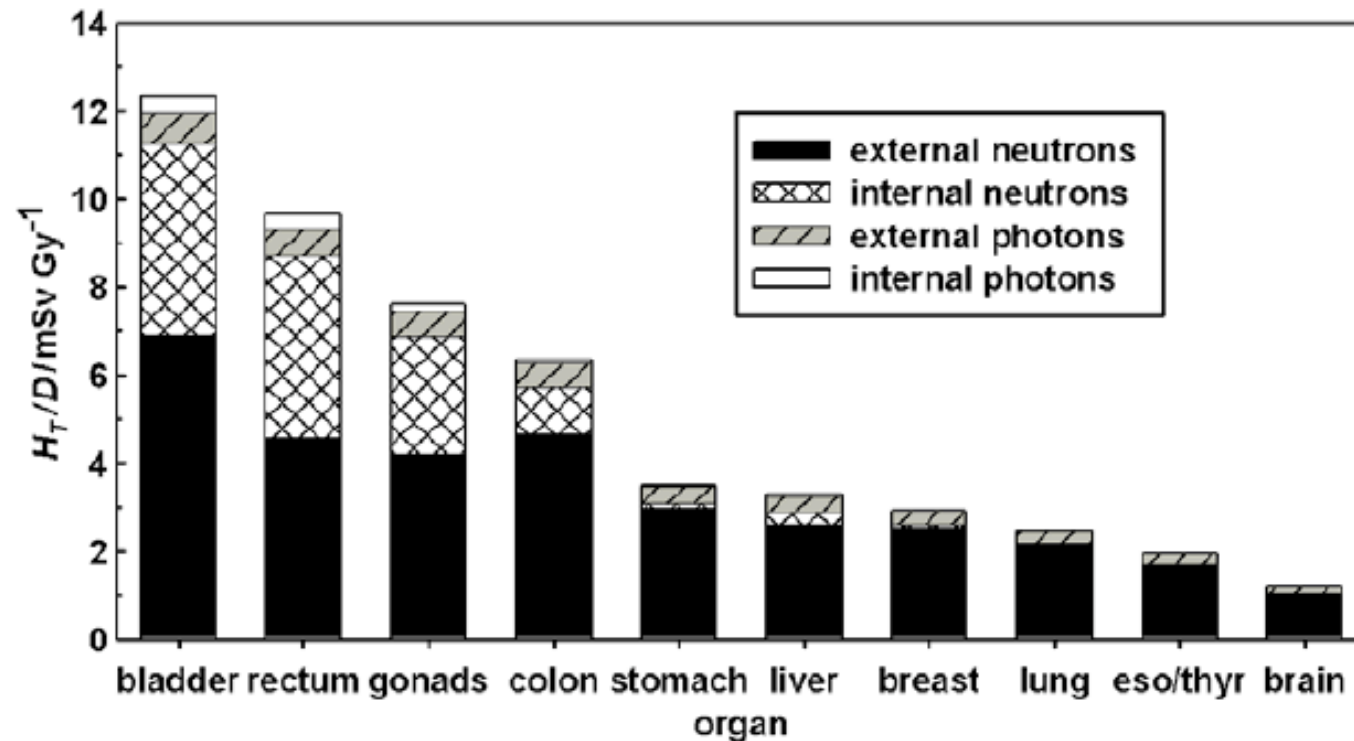


Figure 2. Equivalent dose per therapeutic absorbed dose (H_T/D) in selected organs (arranged in an order of increasing distance from the isocenter) for the simulated prostate treatment, including contributions from stray radiation generated inside the nozzle (external) and inside the patient (internal).

Fontenot et al, Phys Med Biol 2008