Analytical Methods for Normal-Tissue Dose Reconstructions

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Disclosures

I have no conflicts of interest

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Learning Objectives

- Introduction
  - Rationale for modeling stray exposures
  - Current state of knowledge
- Analytical Models for Stray Dose Calculations
  - Show some approaches, results, and codes
  - Proton therapy
  - Photon therapy

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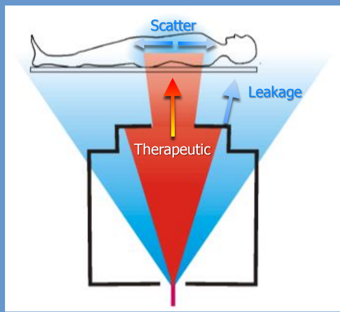
Introduction: Radiotherapy Exposures



Newhauser and Durante, Newhauser WD, Durante M. Assessing the risk of second malignancies after modern radiotherapy. Nat Rev Cancer 11(6):438-48, 2011.

Newhauser WD, Berrington de Gonzalez A, Schulte R, and Lee C. A Review of Radiotherapy-Induced Late Effects Research After Advanced-Technology Treatments, Frontiers in Oncology. Vol 6, article 13 (2016).

Intro: Current State of Knowledge

- Stray exposures vary strongly and depend on a large number of treatment and host factors.
- Lack of high-throughput methods.
- Understanding of physics is emerging.

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Intro: Comparison of Methods for Estimation of Stray Dose

Approach	Accuracy	Speed	Ease of Use	Generalizability of Model
Measurement	★★★	★		n/a
Monte Carlo	★★★	★		★
Analytical: Empirical	★★	★★★	★★★	
Analytical: Physics-based	★★	★★★	★★★	★★★

Which is best?

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Intro: Physics-Based Analytical Models

- Facilitates understanding of the physics.
- Cheap, fast, and generalizable approach.
- Therefore, *potentially* well suited to large-scale, routine, and clinical applications, *e.g.*, prospective clinical trials and epidemiologic studies.

See Newhauser WD, Berrington de Gonzalez A, Schulte R, and Lee C. A Review of Radiotherapy-Induced Late Effects Research After Advanced-Technology Treatments. (Invited review), Frontiers in Oncology. Vol 6, article 13 (2016).

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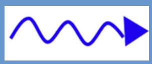
Physics-Based, Analytical Models

PHOTON Beams



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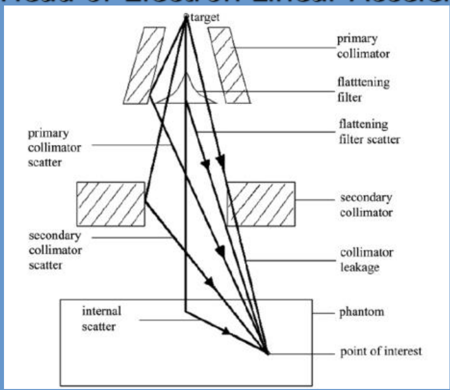
Tx Head of Electron Linear Accelerator



Chofor, Harder, Willborn and Poppe. Phys. Med. Biol. 57 (2012) 1733–1743

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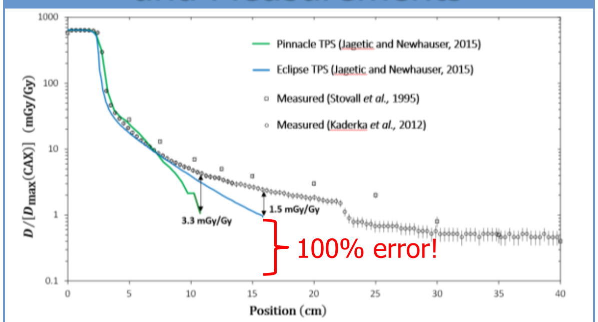
Clinical Photon Planning Systems and Measurements



Jagetic L and Newhauser WD, A simple and fast analytical method to calculate doses to the whole body from external beam, megavoltage x-ray therapy. Phys Med Biol. 60 (2015) 4753–4775.

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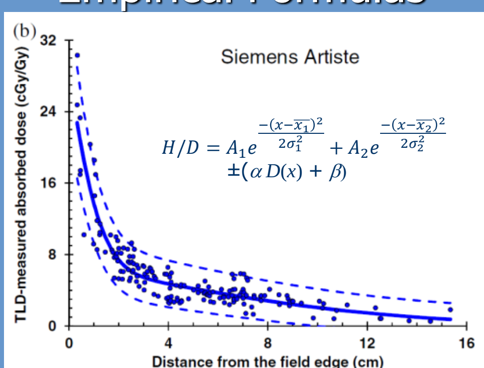
Empirical Formulas



$$H/D = A_1 e^{\frac{-(x-\overline{x_1})^2}{2\sigma_1^2}} + A_2 e^{\frac{-(x-\overline{x_2})^2}{2\sigma_2^2}} \pm (\alpha D(x) + \beta)$$

PJ Taddei, W Jalbout, R Howell, N Khater, F Geara, K Homann, and W Newhauser. Analytical model for out-of-field dose in photon craniospinal irradiation. Phys. Med. Biol. 58 (2013) 7463–7479

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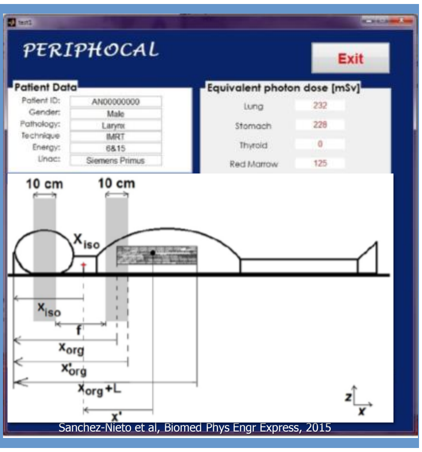
PERIPHOCAL

Stand-Alone Code with Nice User Interface

Versatile

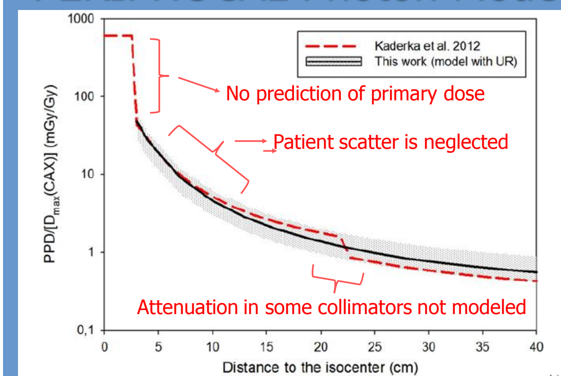
Stylized Phantom

12 equations



Sanchez-Nieto et al, Biomed Phys Engr Express, 2015

PERIPHOCAL Photon Model



Sanchez-Nieto et al, Biomed Phys Engr Express, 2015

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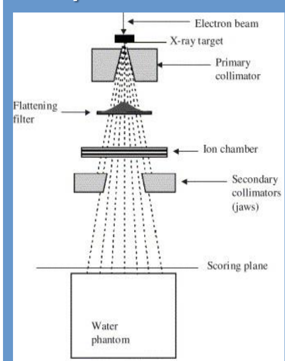
Physics-Based Modeling Approach



Sources (primary and scatter)

Photon Fluence in air

Attenuation in head, phantom

Scattering in head, phantom

Convert fluence to dose

Combine doses

$$D_T = D_P + D_L + D_S$$

(32 Equations)

Jagetic L and Newhauser WD, A simple and fast analytical method to calculate doses to the whole body from external beam, megavoltage x-ray therapy. Phys Med Biol. 60 (2015) 4753–4775

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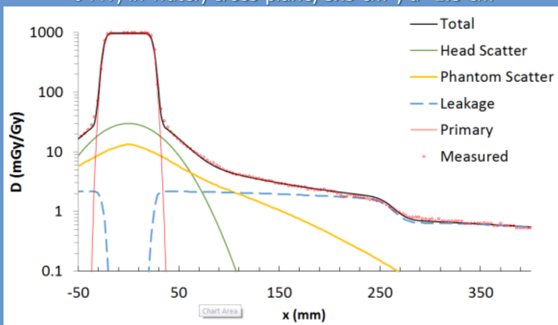
Results: Physics Model Performance

6 MV, in-water, cross-plane, 5x5 cm², d=1.5 cm



Predictions: Jagetic L and Newhauser WD, A simple and fast analytical method to calculate doses to the whole body from external beam, megavoltage x-ray therapy. Phys Med Biol. 60 (2015) 4753–4775..

Measurements: R Kaderka et al. Out-of-field dose measurements in a water phantom using different radiotherapy modalities. Phys Med Biol 57 5059-5074 (2012).

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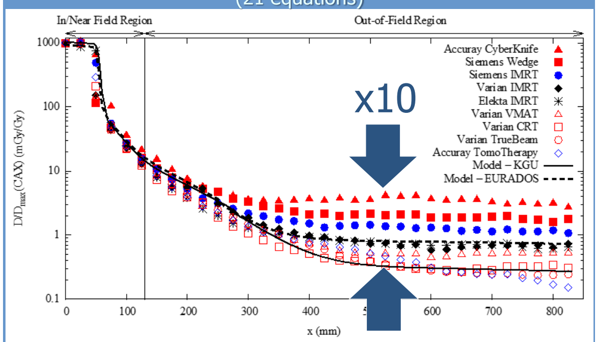
Simpler Physics-Based Analytical Model

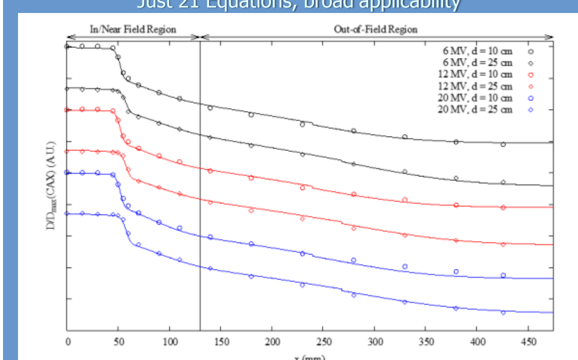
(21 equations)



Schneider CW, Newhauser WD, Wilson LJ, Schneider U, Kaderka R, Miljanic S, Knezevic Z, Stolarcyzk L, Durante M, Harrison RM. A descriptive and broadly applicable model of therapeutic and stray absorbed dose from 6 MV to 25 MV photon beams. Med Phys, just published.

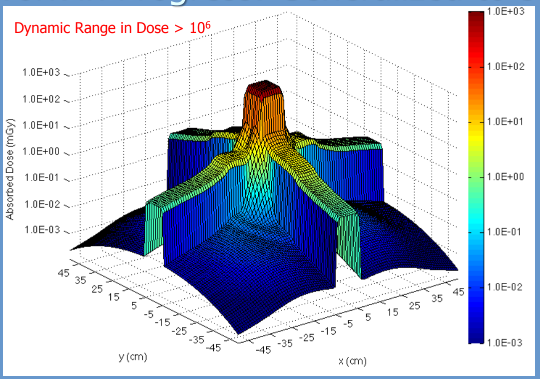
Simpler Physics-Based Analytical Model:

Just 21 Equations, broad applicability



Schneider CW, Newhauser WD, Wilson LJ, Schneider U, Kaderka R, Miljanic S, Knezevic Z, Stolarcyzk L, Durante M, Harrison RM. A descriptive and broadly applicable model of therapeutic and stray absorbed dose from 6 MV to 25 MV photon beams. Med Phys, at press.

Work in Progress: Generalized to 3D



C Schneider, W Newhauser, L Wilson, et al, in preparation.

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Photon Scatter Model from Hauri *et al.*

- CT anthropomorphic phantom
- 6-MV CRT/IMRT/VMAT rectangular (prostate tx fields)
- Therapeutic dose modeled using TPS (Eclipse)
- Leakage and head scatter modeled empirically
- "Mechanistic" model of patient scatter

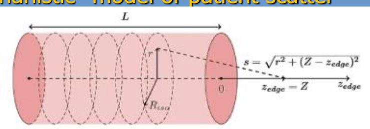

Fig. 2. Sketch of a cylinder consisting of infinitely small sources of strength d.

$$D(Z) = d \cdot \int_0^{2\pi} \int_0^{R_{iso}} |r| \cdot \frac{\exp(-\mu(E_{patient}) \cdot s)}{s^2} dr\, d\varphi$$

Hauri, Halg, and Schneider, Med Phys, 43 1955-1968 (2017)

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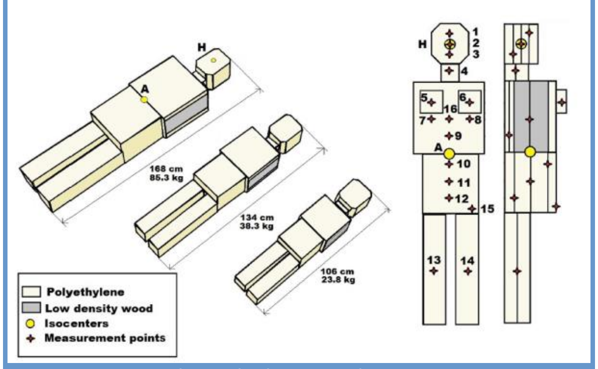
Photoneutrons: Analytical Model with Phantoms



Irazola *et al.*, Physica Medica, at press

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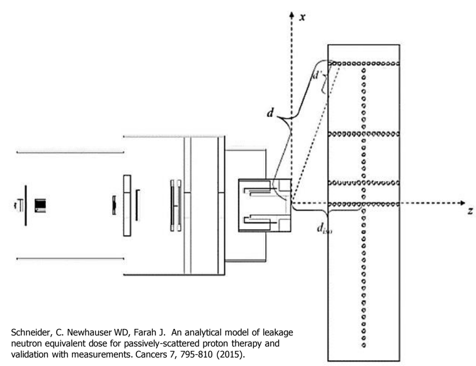
Physics-Based, Analytical Models:

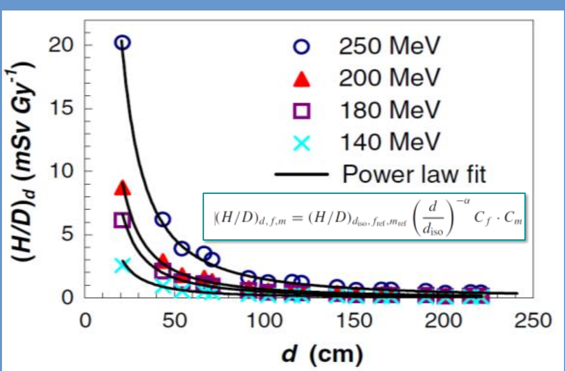
PROTON Beams

Neutron Leakage Exposure From Proton RT



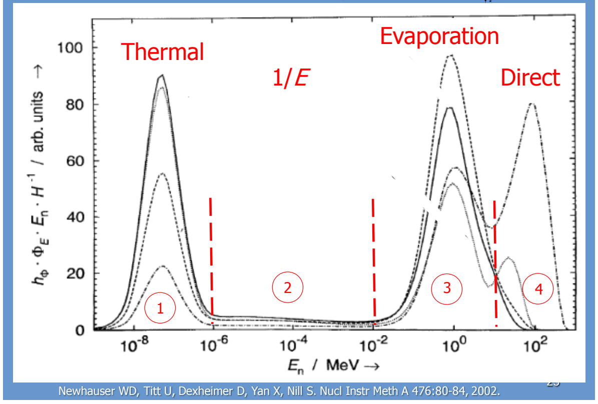
Schneider, C. Newhauser WD, Farah J. An analytical model of leakage neutron equivalent dose for passively-scattered proton therapy and validation with measurements. Cancers 7, 795-810 (2015).

Early Physics-Based Model



Zheng et al. PMB 52 (2007) 4481–4496

Methods: Neutron Spectral Fluence



Newhauser WD, Titt U, Dexheimer D, Yan X, Nill S. Nucl Instr Meth A 476:80-84, 2002.

Simple Model of Neutron Leakage (9 Equations)

$$\left(\frac{H}{D}\right)_p = \left(\frac{H}{D}\right)_{E,iso}\left(\frac{d}{d_{iso}}\right)^{-q}\sum_{i=1}^{4} C_i(E)\exp[-\alpha_i(d'-d'_{iso})]\exp\left[\frac{-(x^2+y^2)d_{iso}^2}{2\sigma_i^2 z^2}\right]$$

Divergence

Attenuation in Phantom

Relative Lateral Intensity

Shape of neutron energy distribution

Perez-Andujar, Zhang, Phil, Newhauser. Prediction of neutron dose equivalent dose source terms for radioprotection in proton therapy. Med. Phys 40, 121714 (2013)

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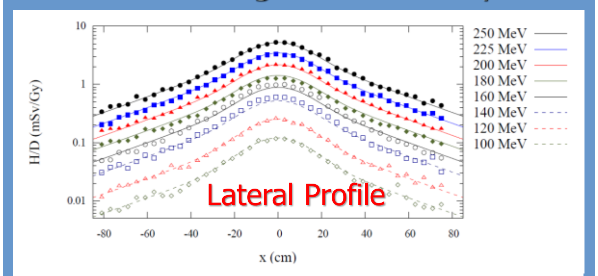
Results of Physics-Based Analytical Model of Leakage Neutron Exposure



Schneider, C. Newhauser WD, Farah J. An analytical model of leakage neutron equivalent dose for passively-scattered proton therapy and validation with measurements. Cancers 7, 795-810 (2015).

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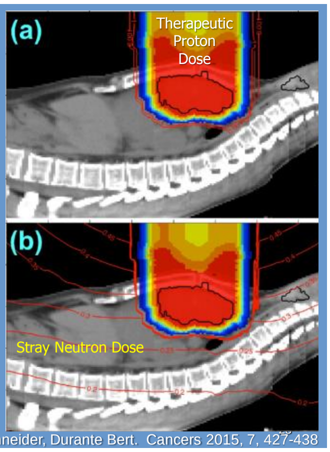
Translation to Clinic Appears *Feasible*

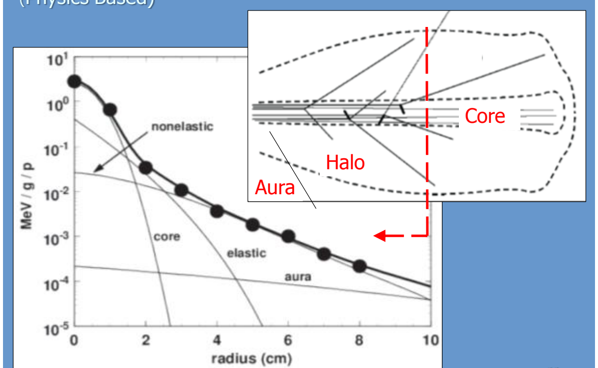


Implemented LSU stray dose model in GSI's TRIP RTP system

Eley, Newhauser, Homann, Howell, Schneider, Durante Bert. Cancers 2015, 7, 427-438

Proton Pencil Beam Model by Gottschalk *et al.*

(Physics Based)



B Gottschalk, E Cascio, J Daartz and M Wagner. arXiv:1412.0045v3 [physics.med-ph] 29 May 2015

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Discussion

- Rapid progress toward understanding of physical processes of stray exposures.
- A variety of physics-based analytical models have emerged in recent years with promising results.
- Currently, we are in the late R&D phase and will soon enter translation phase.

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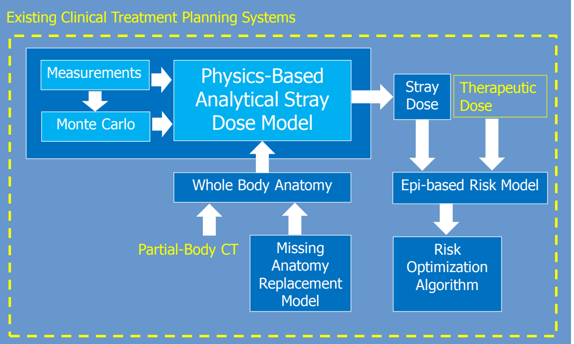
Connections and Integration …



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Thank You

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Selected Recent Review Papers

- Newhauser WD, Schneider C, Wilson L, Shrestha S and Donahue W. A review of analytical models of stray radiation exposures from photon- and proton-beam radiotherapies (invited paper). Radiat Prot Dosim. (in review).
- Newhauser WD, Berrington de Gonzalez A, Schulte R, and Lee C. A Review of Radiotherapy-Induced Late Effects Research After Advanced-Technology Treatments. (Invited review), Frontiers in Oncology. Vol 6, article 13 (2016).
- Newhauser WD and Zhang R, The physics of proton therapy (Invited review). Phys Med Biol. 60 (2015) R155–R209.

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