Computational Tools to Calculate X-ray Imaging Dose & Assess Radiotherapy Treatment Beam Modulation

Medical Physics

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Part 1:

Development & Validation of a Kilovoltage (kV) Dose Computation Method

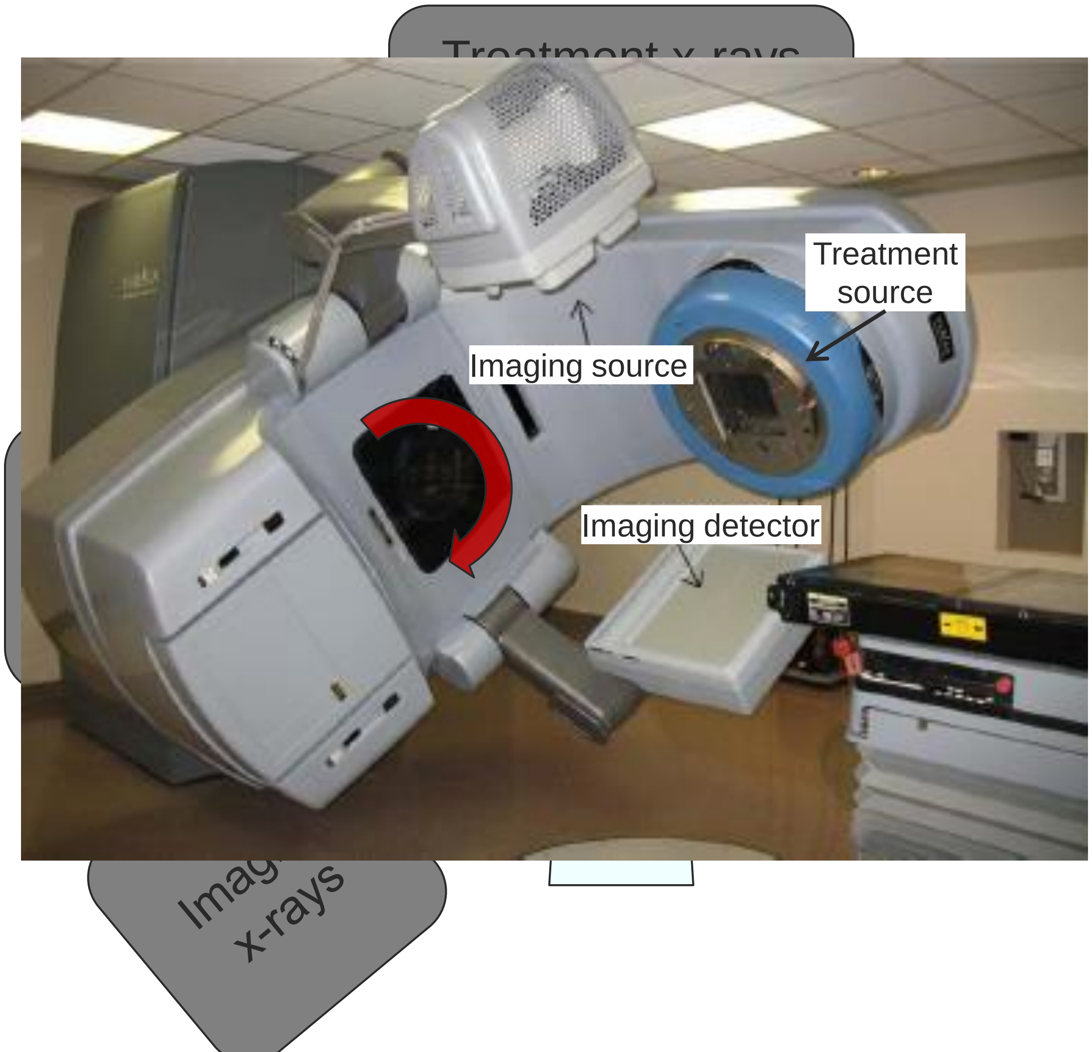
Background: Medical Imaging & Kilovoltage (kV) X-rays

X-ray Radiography

Fluoroscopy

CT Scans

Background:
Image Guided Radiotherapy



- Treatment Goal:
  - Maximize dose to tumor
  - Avoid healthy tissue
- Imaging to locate tumor and adjust patient setup
- Patients imaged daily can accumulate considerable dose
  - Skin (max. dose deposited at surface)
  - Bone (photo-electric effect dominates)

Background & Motivation

- Dose from imaging can:
  - Increase stochastic effects (cancer risk)
  - In radiotherapy: Push planned dose to healthy tissues beyond their tolerance for a given side effect
- Need to:
  - Assess and monitor x-ray dose each patient receives from kV-imaging

Overall Research Goal

- Develop and validate an approach to compute patient-specific dose from a kV imaging device

- Method must be:
  - Accurate
  - Clinically feasible
    - Patient specific
    - Calculate dose within reasonable time

Method for Computing kV Dose

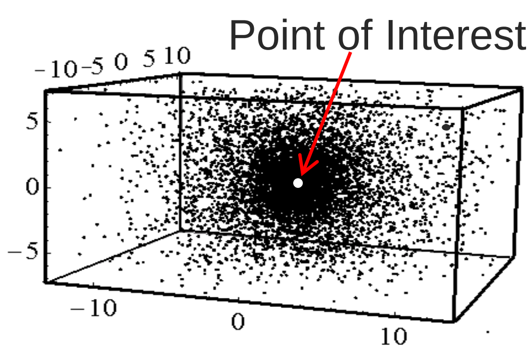
- Developed in-house software (kVDoseCalc) to compute dose deposited by kV x-rays[1]
- Dose is computed by numerically solving the linear Boltzmann transport equation (LBTE)
- Validated using MCNP, EGSnrc, and experimental measurements[1,2]

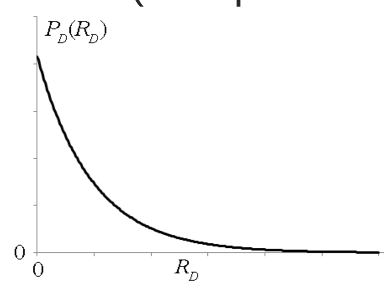
[1] Kouznetsov, A. and **Tambasco, M.**, 2011, A hybrid approach for rapid, accurate and direct kilovoltage radiation dose calculations in CT voxel space, *Medical Physics,* 38(3), 1378-1388.

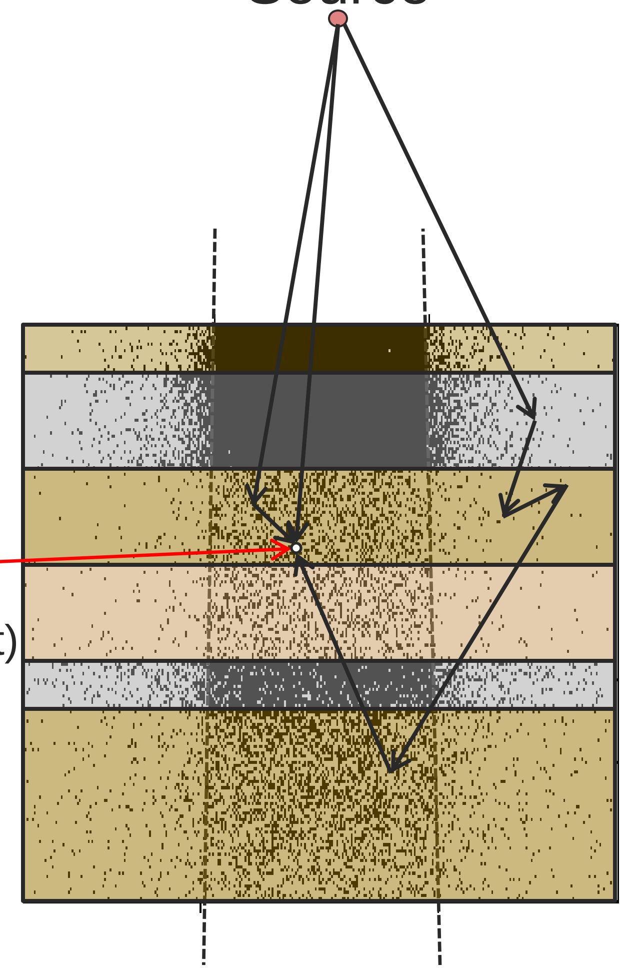
[2] Poirier, Y., Kouznetsov, A., and **Tambasco, M.**, 2012, A simplified approach to characterizing a kilovoltage source spectrum for accurate dose computation, *Medical Physics,* 39(6).

Overview: Computational Approach

- Source defined by spectrum and spatial fluence
- Deterministic ray transport
  - Primary component
- Stochastic computation
  - 1-Scattered
  - N-Scattered







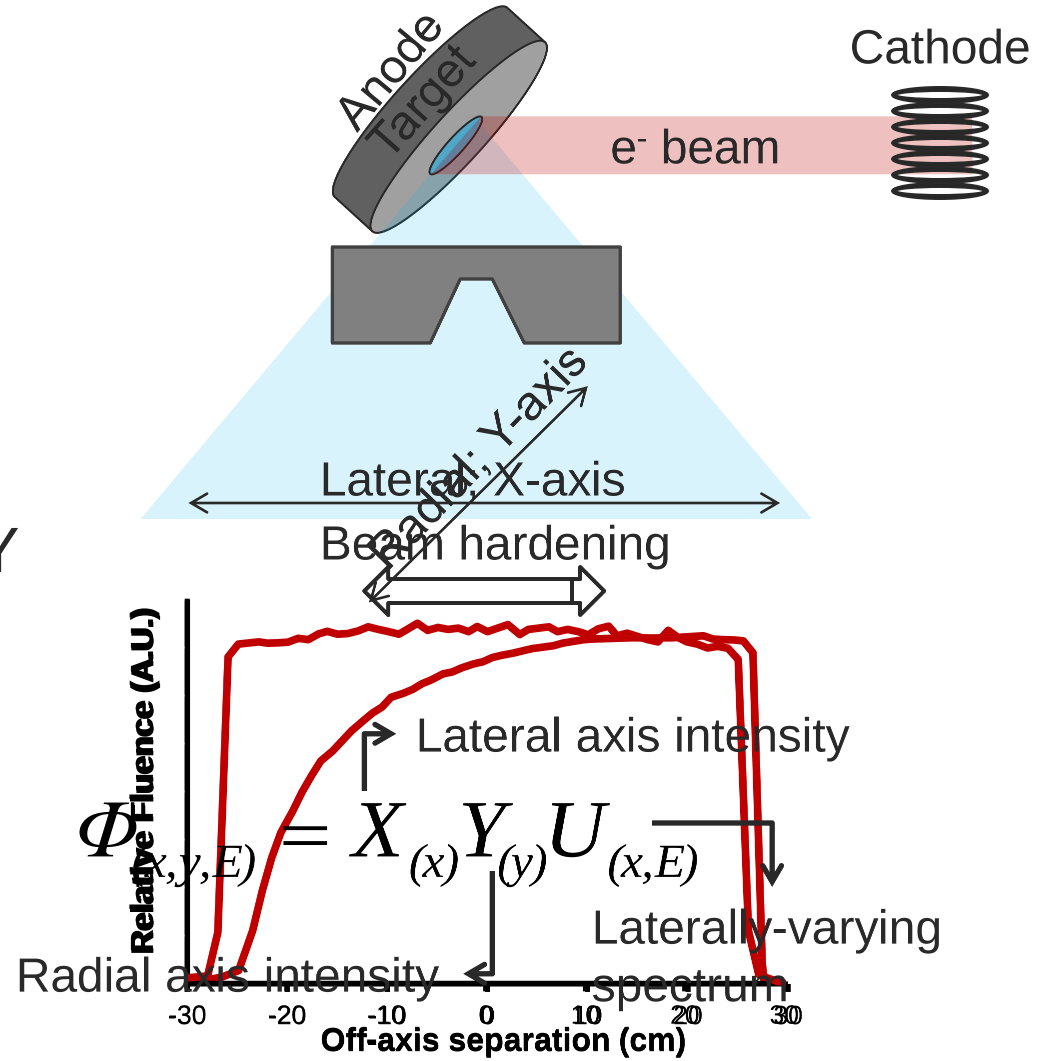
Source Characterization

- Spatial fluence
- Spectrum at different spatial positions
- Requirement:
  - Characterization needs to be clinically feasible

Properties of a kV x-ray source

- Photon intensity
  - Varies along X
  - Varies along Y
- Spectrum
  - Varies along X
  - Does not vary along Y

- Proposed source model :



$$\Phi_{(x,y,E)} = X_{(x)} Y_{(y)} U_{(x,E)}$$

Monte Carlo graphs obtained from :
Ding, G.X, Duggan, D.M., Coffey, C.W., *Characteristics of kilovoltage x-ray beams used for cone-beam computed tomography in radiation therapy*, Phys. Med. Biol. **52**, 2007 p. 1595-1615

Determination of $U_{(x,E)}$

- In principle:

  The entire spectrum should be known

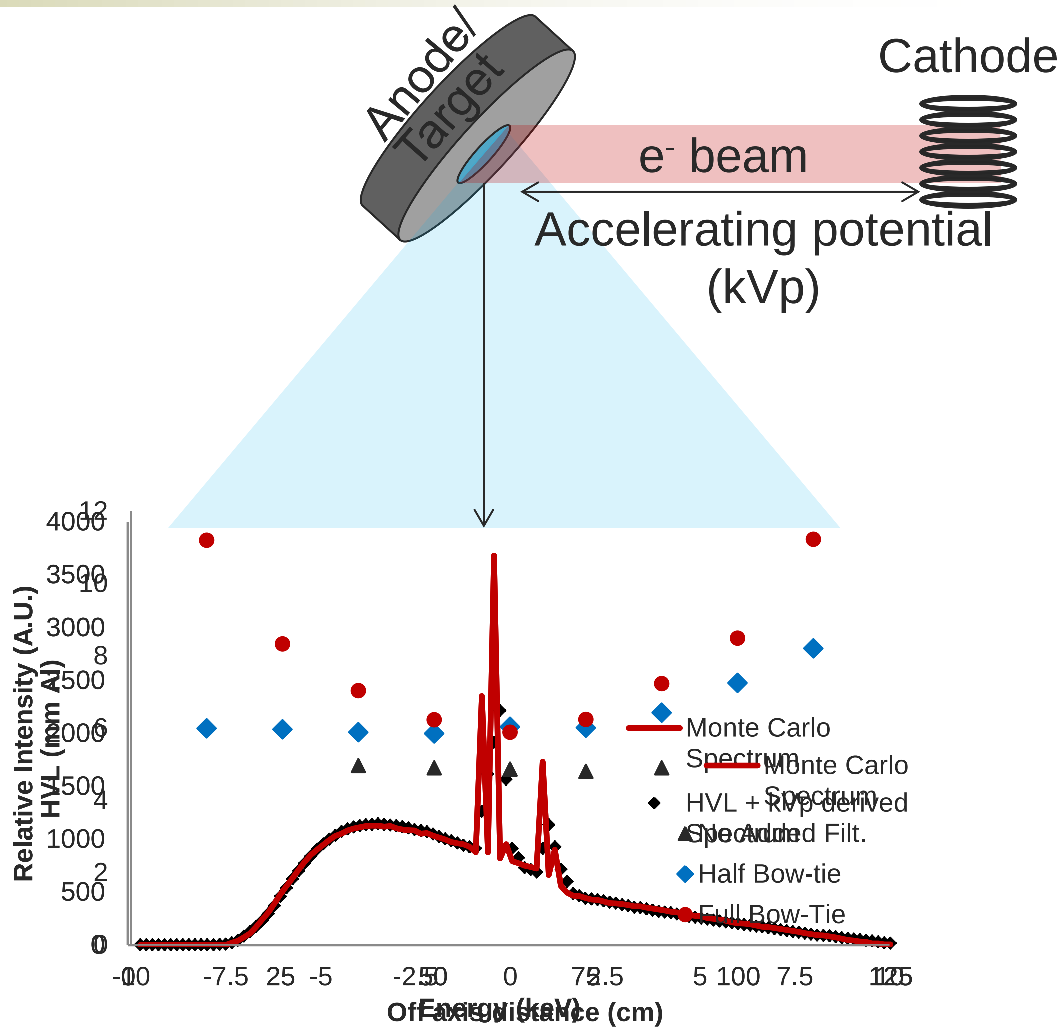
- In practice:

  Half-value layer (HVL) and kVp used to describe beam

- Use kVP + HVL to determine spectrum

  Matlab Freeware Spektr

  Validated for open beams within 4-6%*



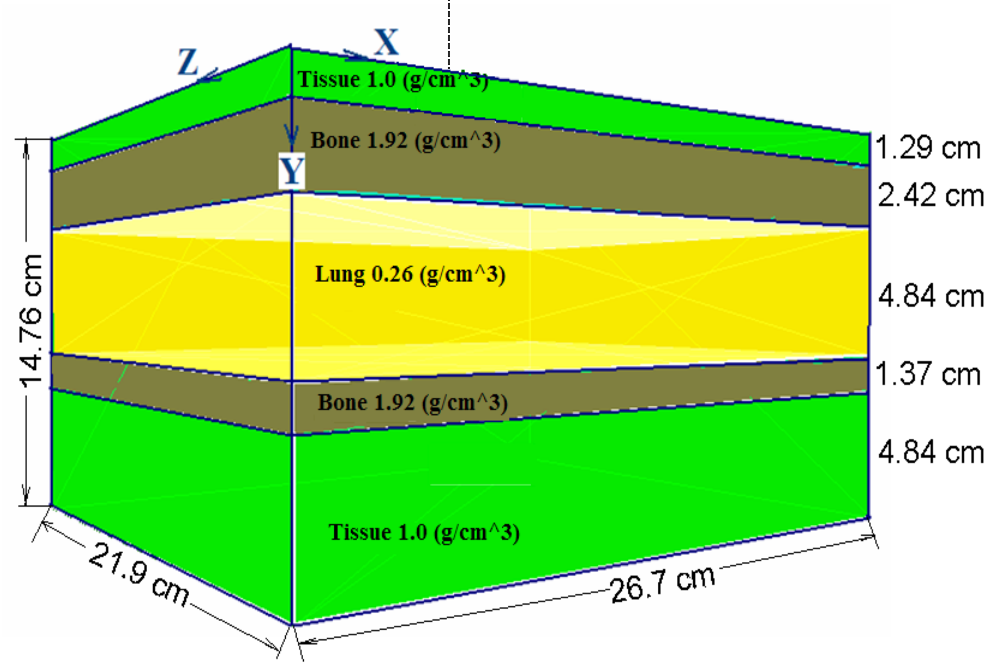
*Y. Poirier, A. Kouznetsov, M. Tambasco, A simplified approach to characterizing a kilovoltage source spectrum for accurate dose computation, Med. Phys. 39 (6), 2012 p.3041-3050

Validation:
Computational & Experimental

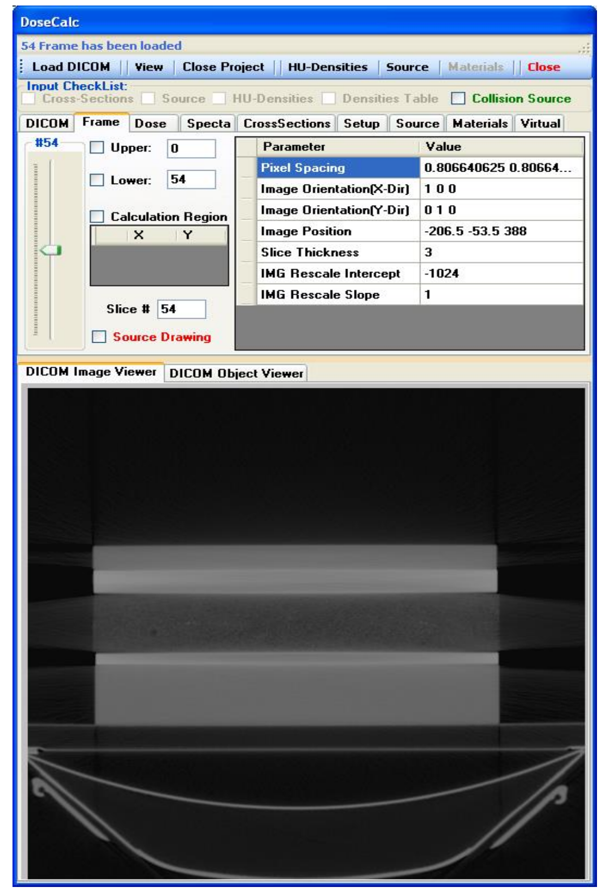
Point Source
(Monte Carlo derived spectrum for Varian® OBI System)*

SSD = 100 cm

FS = 10×10 cm^2



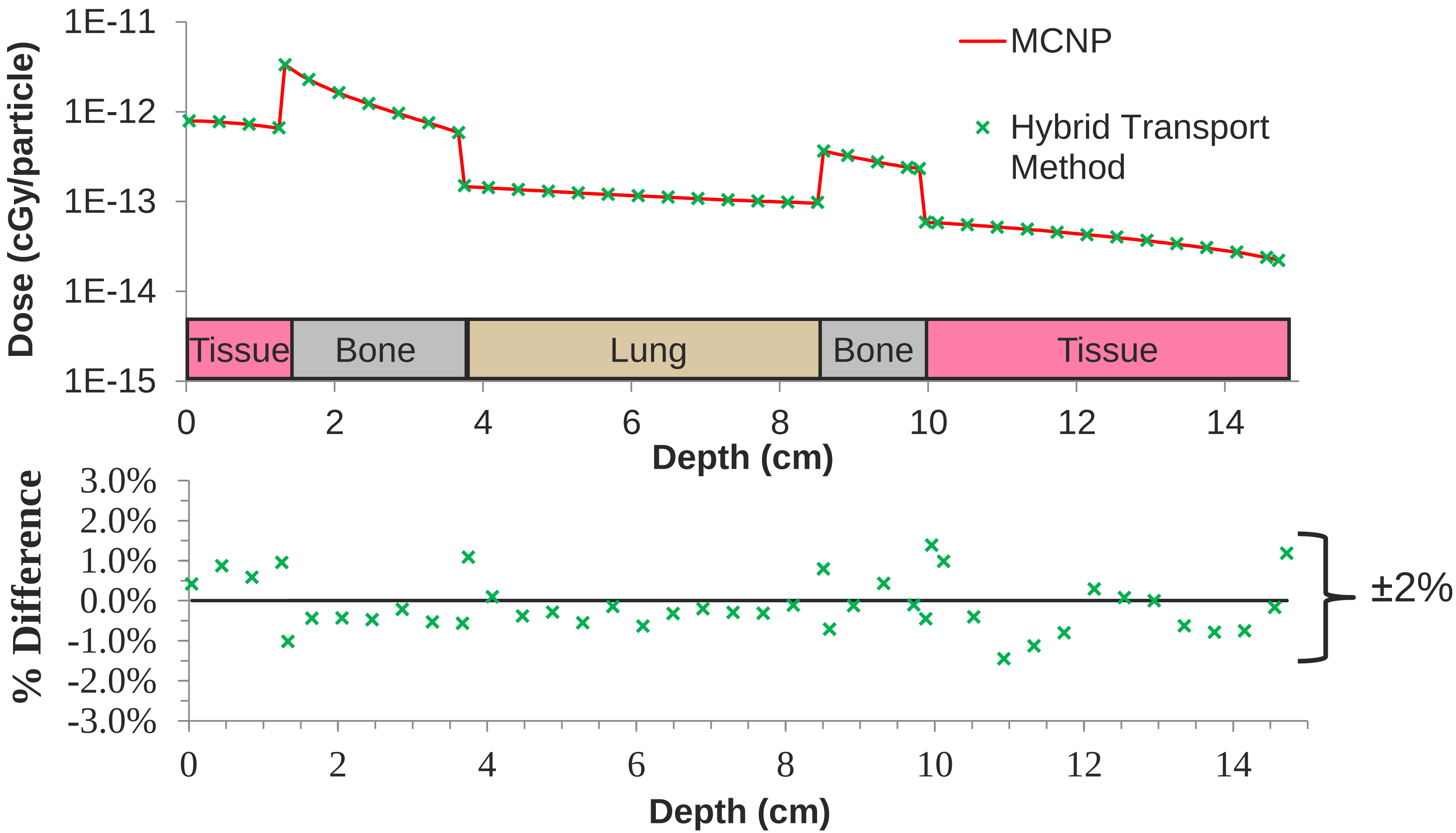
Validation Phantom



kVDoseCalc GUI

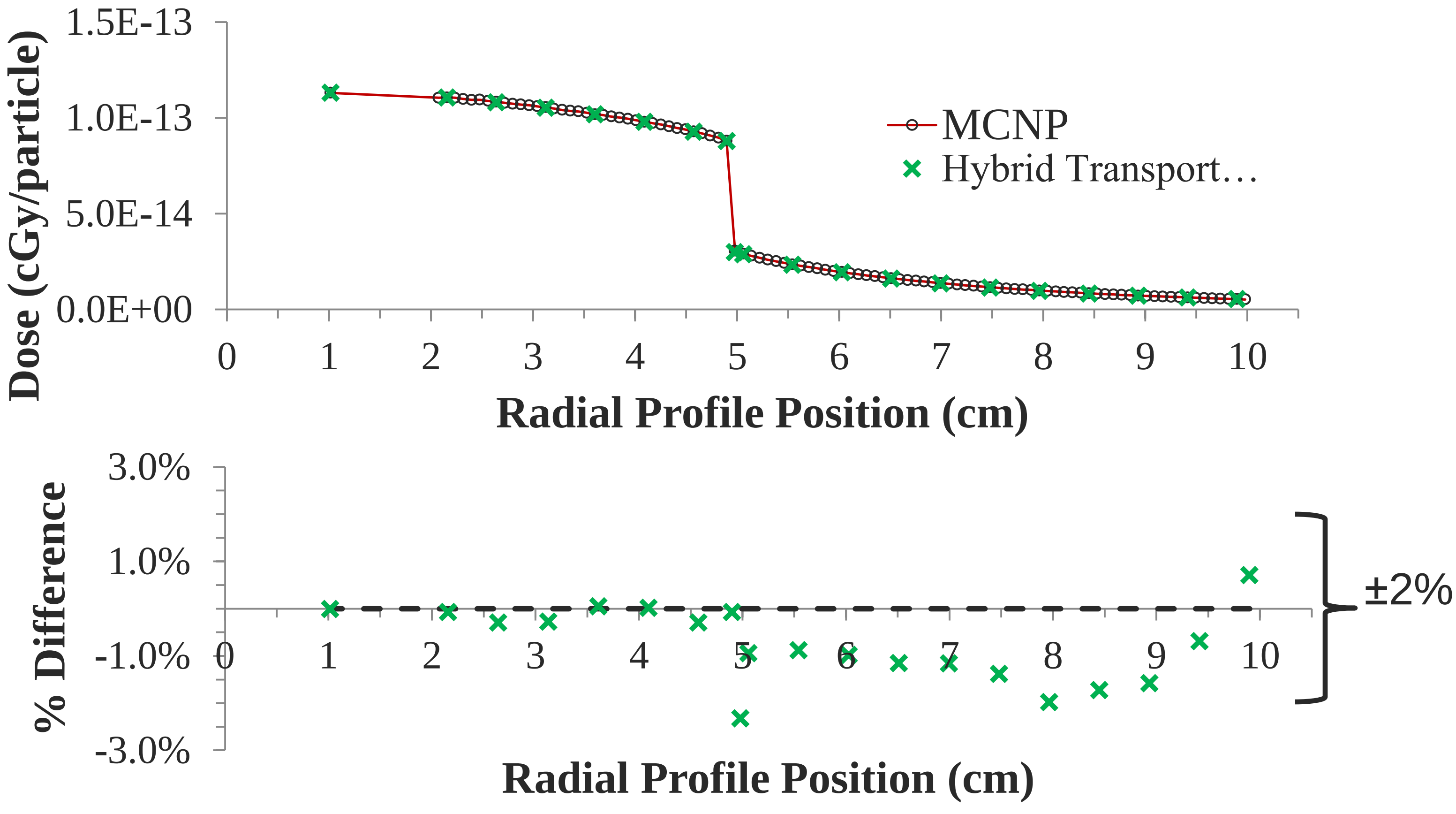
*Ding GX, et al., Phys. Med. Biol. 52 (2007) 1595-1615

MCNP/EGSnrc Validation:
Central Axis Depth Dose



Kouznetsov, A, Tambasco, M. (2011) *Medical Physics, 38*(3), 1378-1388.

Computational Validation:
Profile at Centre of Lung Slab



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Source: Spectrum

- Computational validation assumed point spectral source
- HVL and kVp do not uniquely determine spectrum
- Performed sensitivity analysis
  - Showed that HVL and kVp are sufficient to characterize a kV source spectrum

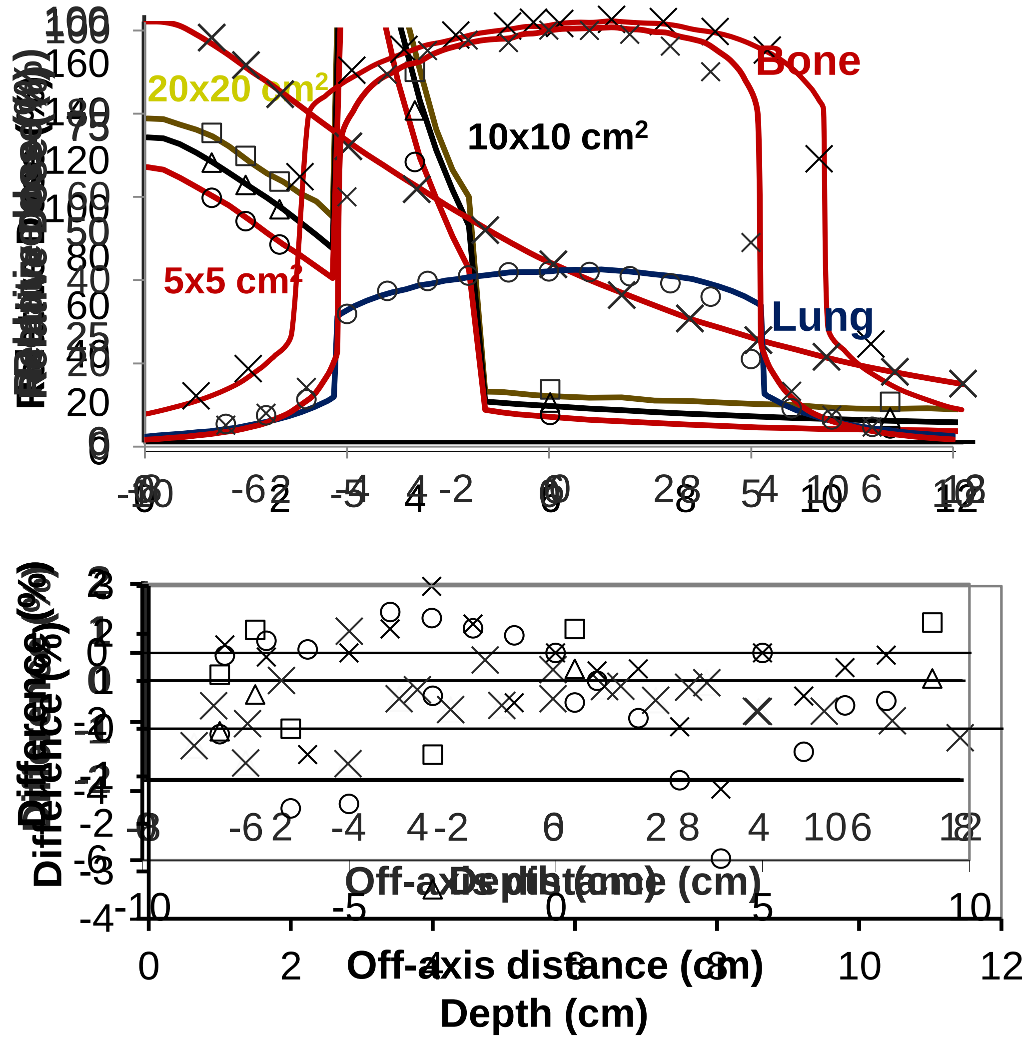
Poirier, Y., Kouznetsov, A., and **Tambasco, M.**, 2012, *Medical Physics,* 39(6).

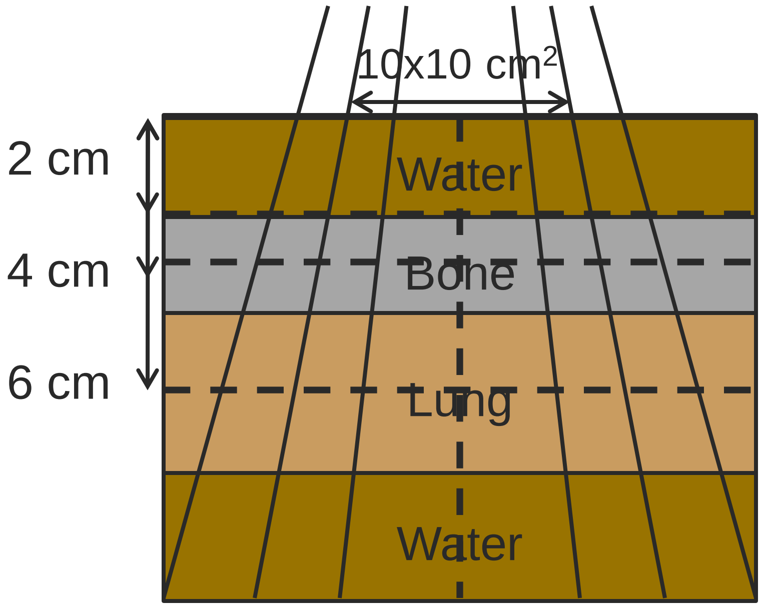
Sensitivity Analysis Conclusions

- Difference in dose computation between Spektr-derived and MC spectrum is $\leq 0.1\%$
- Experimental variation of HVL (0.1-0.2 mm Al) changes dose computation accuracy by at most 1%
- Experimental variation of kVp (1-2 kVp) changes computation accuracy by at most 1%
- Possible to characterize spectrum based on HVL and kVp within 1.2% accuracy

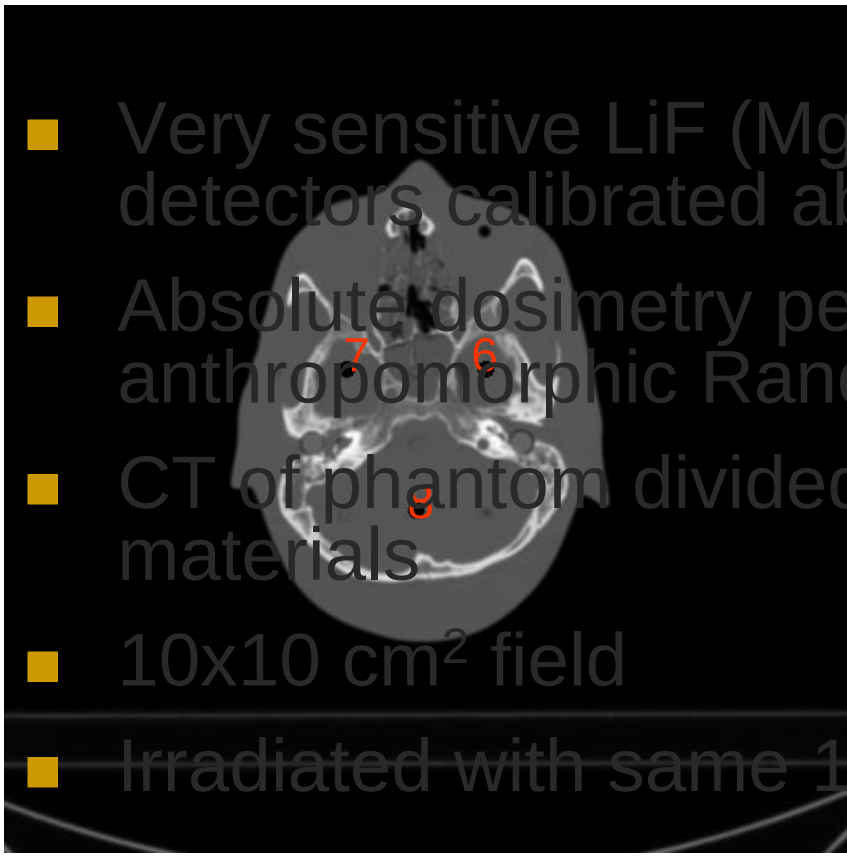
Experimental Validation - Relative

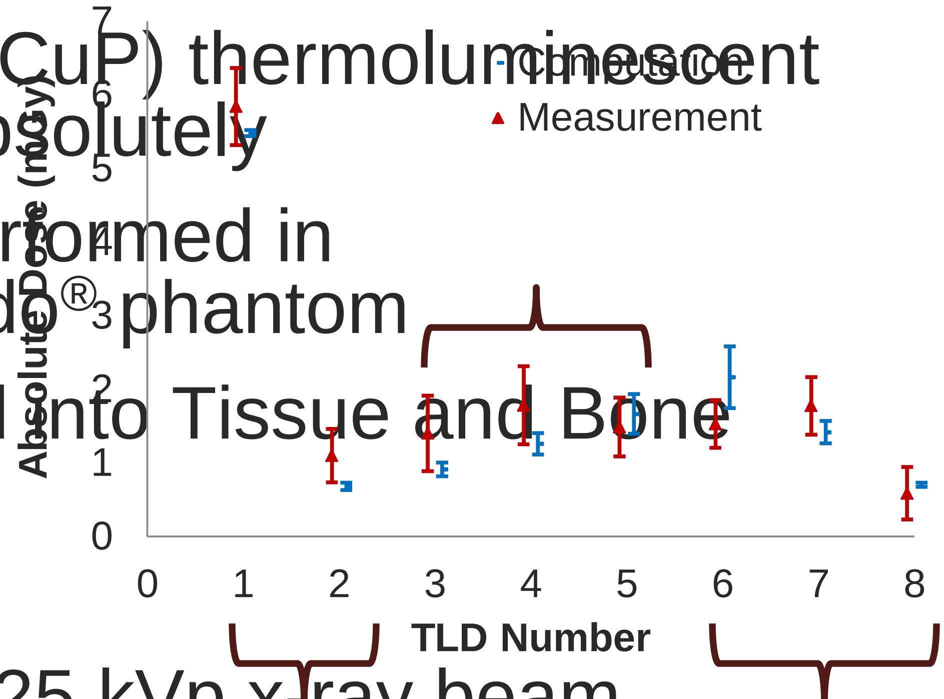
- Measurements are made with 0.6 cc Capintec ion chamber
- Radiographic pulse of 125 kVp, 160 mA 160 ms





Experimental Validation - Absolute

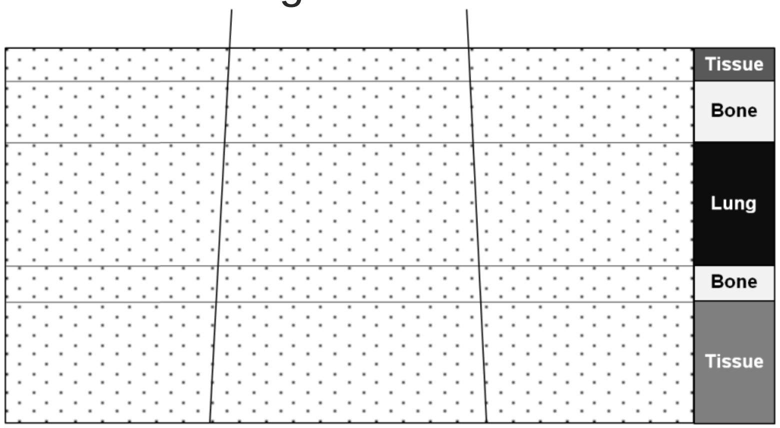




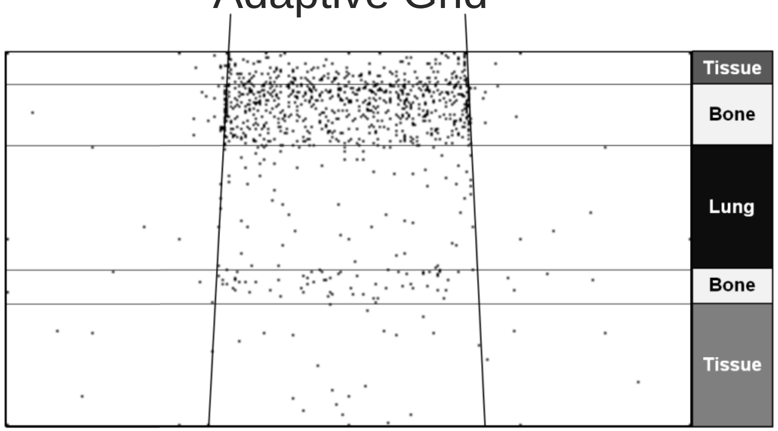
- Very sensitive LiF (MgCuP) thermoluminescent detectors calibrated absolutely
- Absolute dosimetry performed in anthropomorphic Rando® phantom
- CT of phantom divided into Tissue and Bone materials
- 10x10 cm^2 field
- Irradiated with same 125 kVp x-ray beam

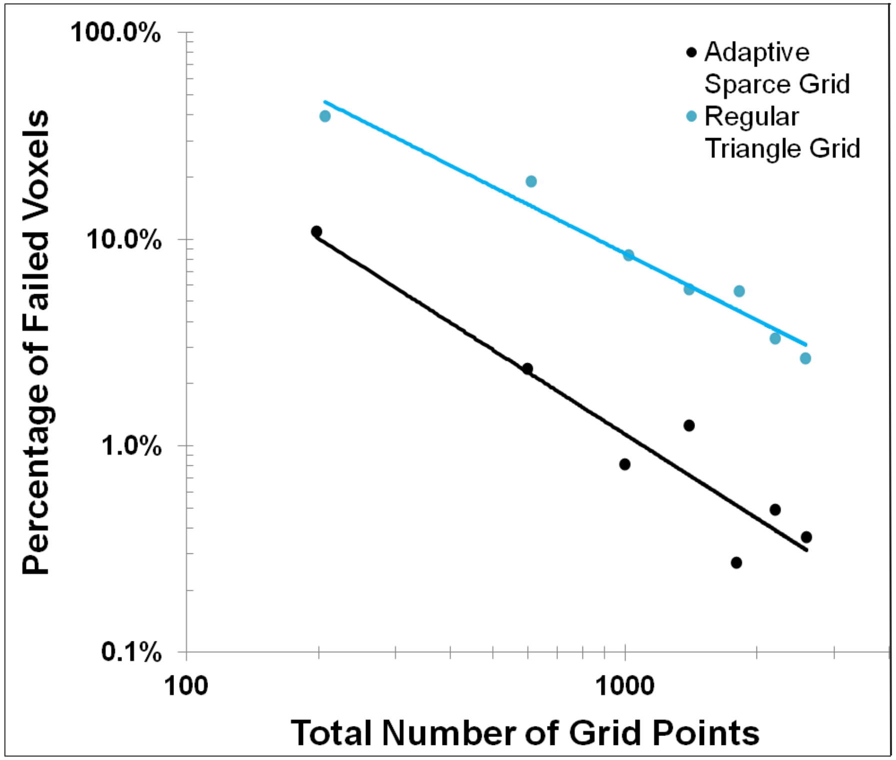
Dose Interpolation:
Adaptive Sparse Grid

Regular Grid



Adaptive Grid

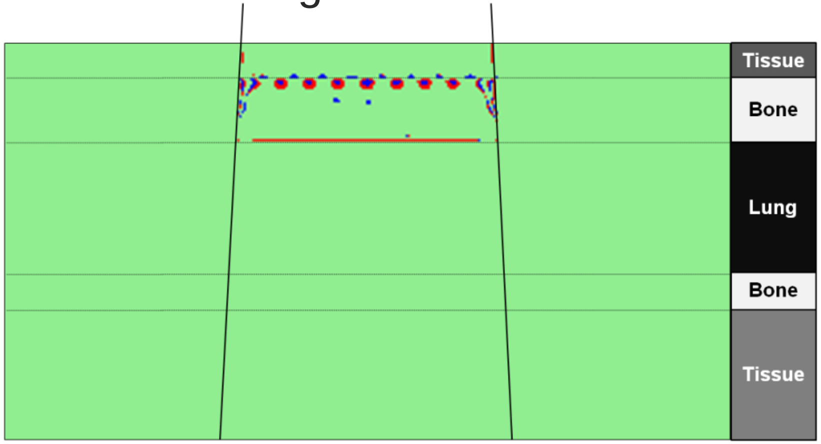




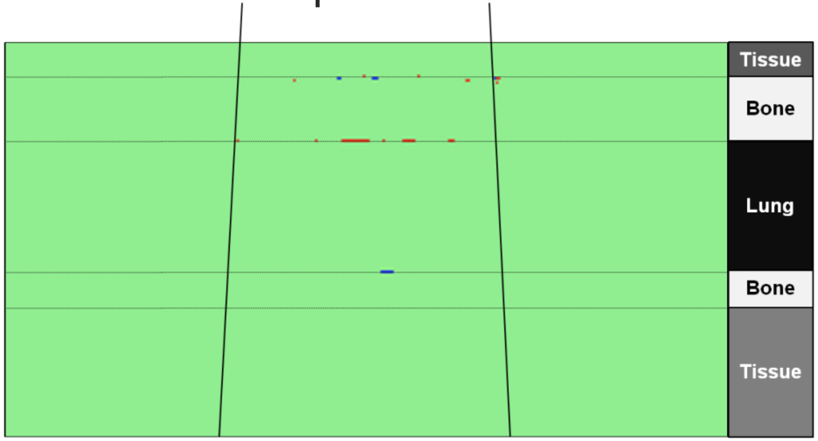
Gamma Analysis (%DD = 2%, DTA = 2 mm)

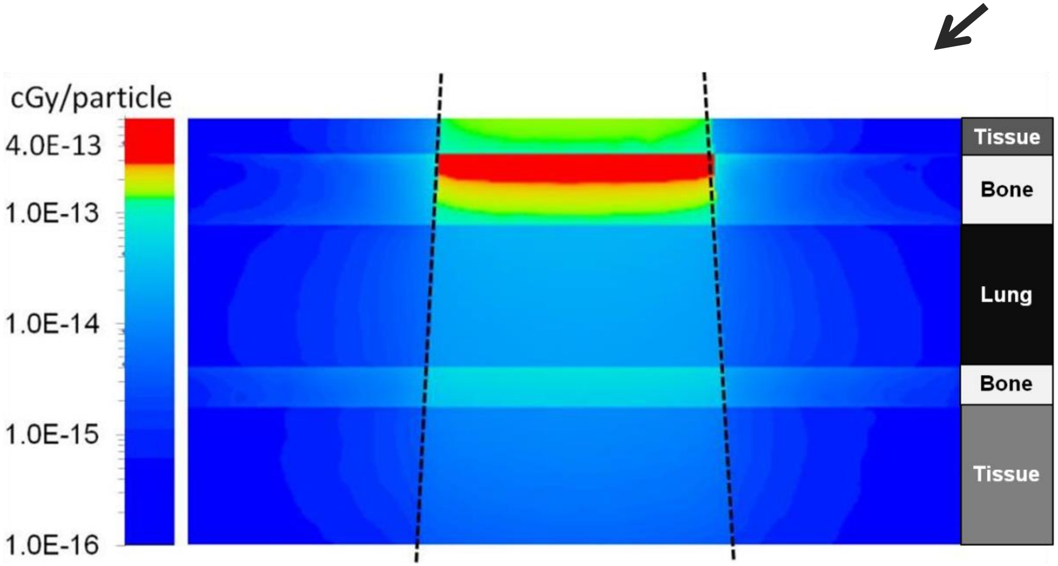
Dose Interpolation:
Error Distribution & Dose Map

Regular Grid



Adaptive Grid





Progress summary

- Sensitivity Analysis & Source Characterization
  - HVL and kVp can be used to characterize source spectrum
  - Developed clinically feasible method to characterize spatial fluence as input for kVDoseCalc
- Relative dosimetry
  - Homogeneous phantom : agrees within 2%
  - Heterogeneous phantom : agrees within 4%
- Absolute dosimetry Rando® phantom
  - Complex geometry
  - Agreement within experimental uncertainty

Work in Progress

- Adaptive Grid Implementation
  - To speed up calculations and maintain accuracy
- Incorporate added filtration (e.g. half and full bowtie filters) on source characterization
- Model and validate our method for radiography, fluoroscopy, CT, and CBCT imaging
  - Anthropomorphic phantom for dose validation
- Adapt code for GPU computation

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