Public Health England

Use of voxel phantoms for CT dosimetry

Jan Jansen

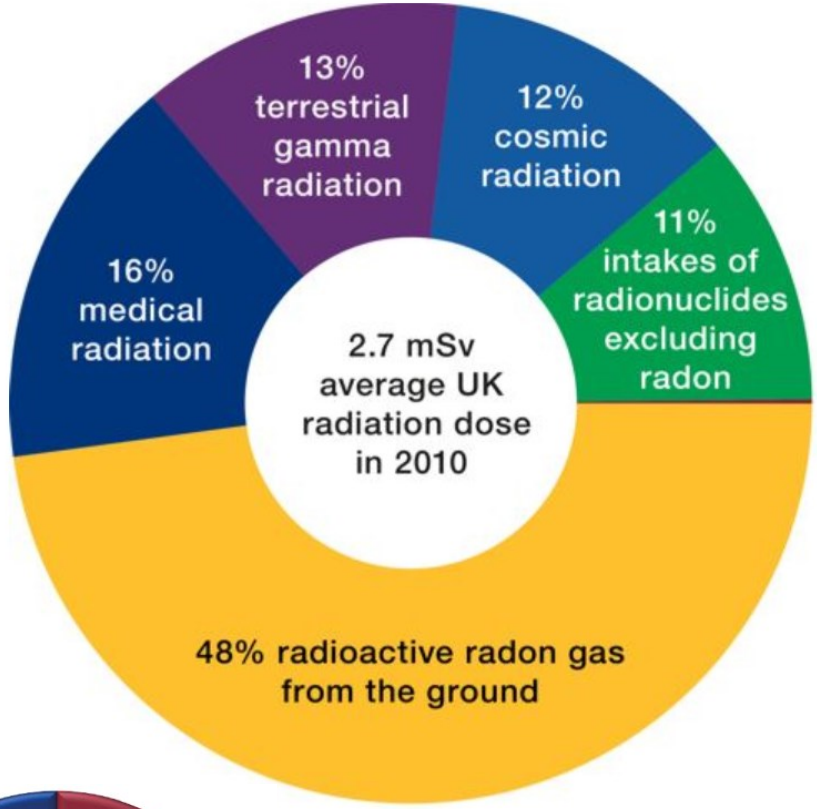
11th EURADOS Winter School
Lisbon, Portugal

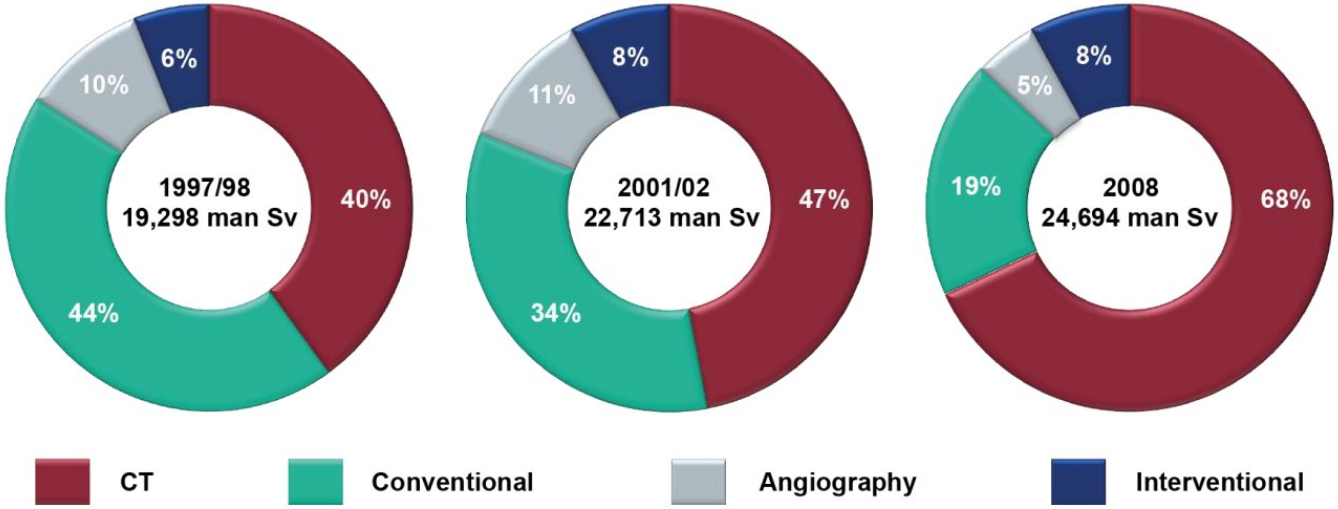
8th February 2018

Public Health England

Introduction

Ionising Radiation Exposure of the UK Population: 2010 Review.
W B Oatway, A L Jones, S Holmes, S Watson and T Cabianca.
PHE-CRCE-026, 2016





Public Health England

Introduction

- Annual collective effective doses from CT are still increasing
- NRPB SR250 data from the early 1990s (Paul Shrimpton)
- Support medical physicists in estimating organ and effective doses for CT examinations
- ImPACT CT Patient Dosimetry Calculator (St Georges Hospital, London)
- ImPACT match factor introduced to match modern scanners to SR250 data

Public Health England

Introduction

- Modern scanners
  - Spiral
  - Multi-row detectors
- Change in anthropomorphic phantoms
  - From mathematical (MIRD) phantoms to voxel phantoms
- Change in ICRP effective dose (E) definition
  - Publication 60 (1990) versus Publication 103 (2007)
  - New risk and remainder organs have been added
- Radiation transport codes
  - Voxel phantoms enabled
  - From workstation to PC-cluster
- Computer equipment
  - Increased CPU speed, multi-core, more memory

Public Health England

PC Cluster

- 7 nodes
  - Supermicro H8DAR-T/E
  - 2x Dual-Core AMD Opteron 265 1.8 GHz
- 4 nodes
  - Supermicro H8DMR-82
  - 2x Dual-Core AMD Opteron 2222 3.0 GHz
- Calculation nodes
  - 250 GB hard disk
  - 8 GB RAM
- Server node
  - Areca ARC-1110 RAID controller
  - 4x 250 GB hard disks
- Netgear Prosafe GS116 Ethernet switch
- 2x D-Link DKVM-8E KVM switch
- Sony AIT 2 Turbo tape driver

Public Health England

Software and phantoms

- NRPB18+ with NRPB-SR250 data (Old data)
- Radiation transport code
  - MCNPX 2.7.0 (Los Alamos National Laboratory)
- Phantoms
  - Adult Male (ICRP-110), Adult Female (ICRP-110)
    - Bone correction factors, according to Johnson et al. (ICRP-116)
    - 50 micrometre thick medullar cavity implemented in lattice
  - MIRD like phantoms
    - NRPB18+DJ, NRPB18+, HPA18+
  - CTDI phantoms
  - Free in air geometry
- CT Scanners

Public Health England

CT scanners

Models	Tube voltage (kV)	Bow-Tie filter	Fan
Bsp16Elite+Optima660	80, 100, 120, 140	Large, Small	
CT750 HD + VCT	80, 100, 120, 140	Large, Medium, Small	
Brilliance 64	80, 120, 140		
iCT 256	80,100, 120, 140	Body, Head, Baby	
Definition	80,100, 120, 140	Body, Head	Full, Small
Emotion 6	80, 110, 130		
Sensation 16	80,100, 120, 140	Body, Head	
Sensation 64 + Open ”	80,100, 120, 140		
Aquilion 16	80, 100, 120, 135	DR, L, S	

Public Health England

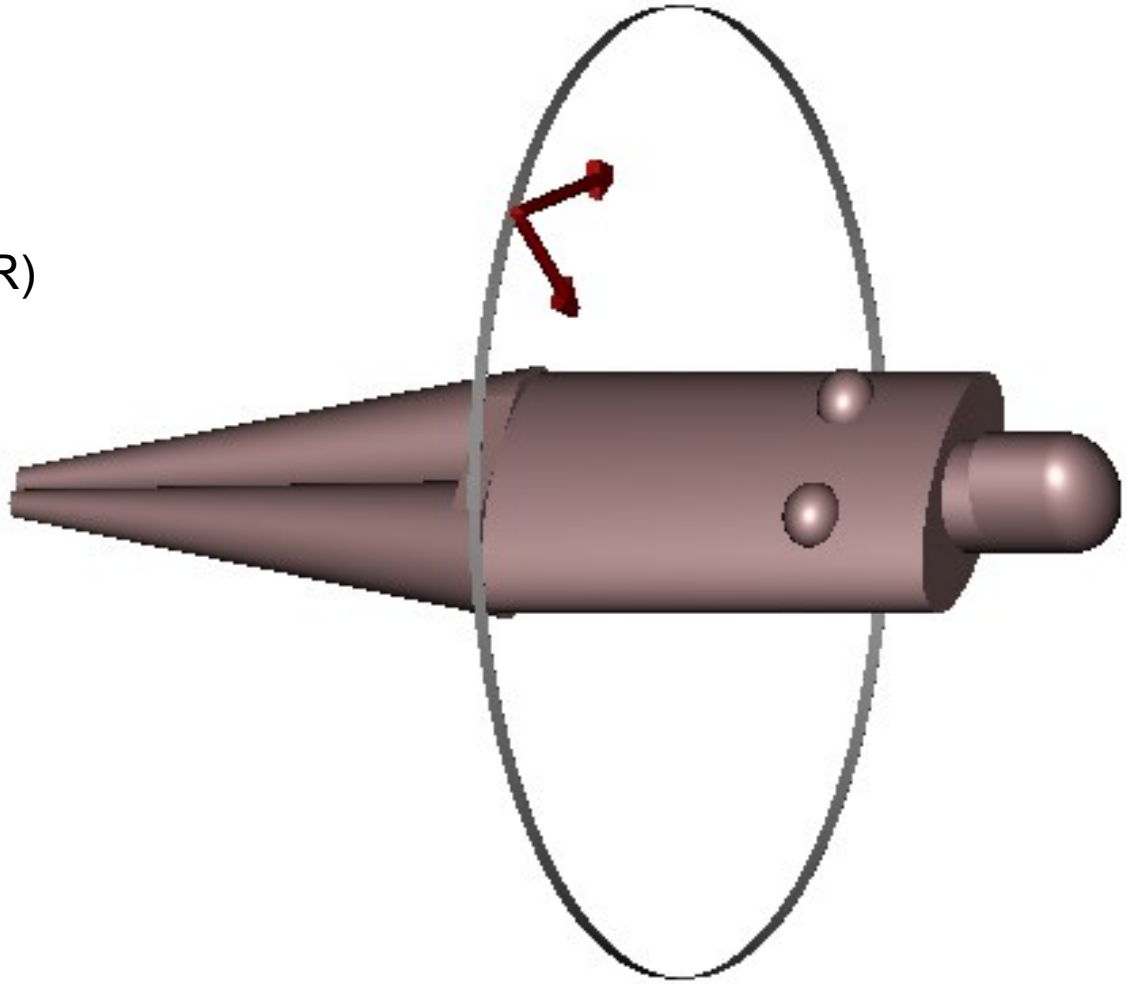
Golem, AP Parallel Beam, 10^7 100 keV Photons

Processor frequency (GHz)	MCNP code	F90 / F95 compiler	Optimization flag	Set-up time (min)	Run-time (min)	Post-process time (min)
1.8	MCNP5 (v1.40)	PGI	fastsse	1621 ± 16	133 ± 6	0.01 ± 0.01
1.8	MCNP5 (v1.40)	Intel	default	909 ± 52	119 ± 13	0.02 ± 0.01
1.8	MCNPX (v2.5.0)	PGI	default	0.98 ± 0.01	166.4 ± 0.7	0.00 ± 0.01
1.8	MCNPX (v2.5.0)	Intel	default	0.84 ± 0.04	141 ± 12	0.02 ± 0.01
1.8	MCNPX (v2.6.0)	Intel	default	0.81 ± 0.05	126 ± 18	0.02 ± 0.01
3.0	MCNPX (v2.6.0)	Intel	default	0.46 ± 0.02	75 ± 3	0.02 ± 0.01

Public Health England

X-ray Source Model 1: NRPB-SR250 (David Jones)

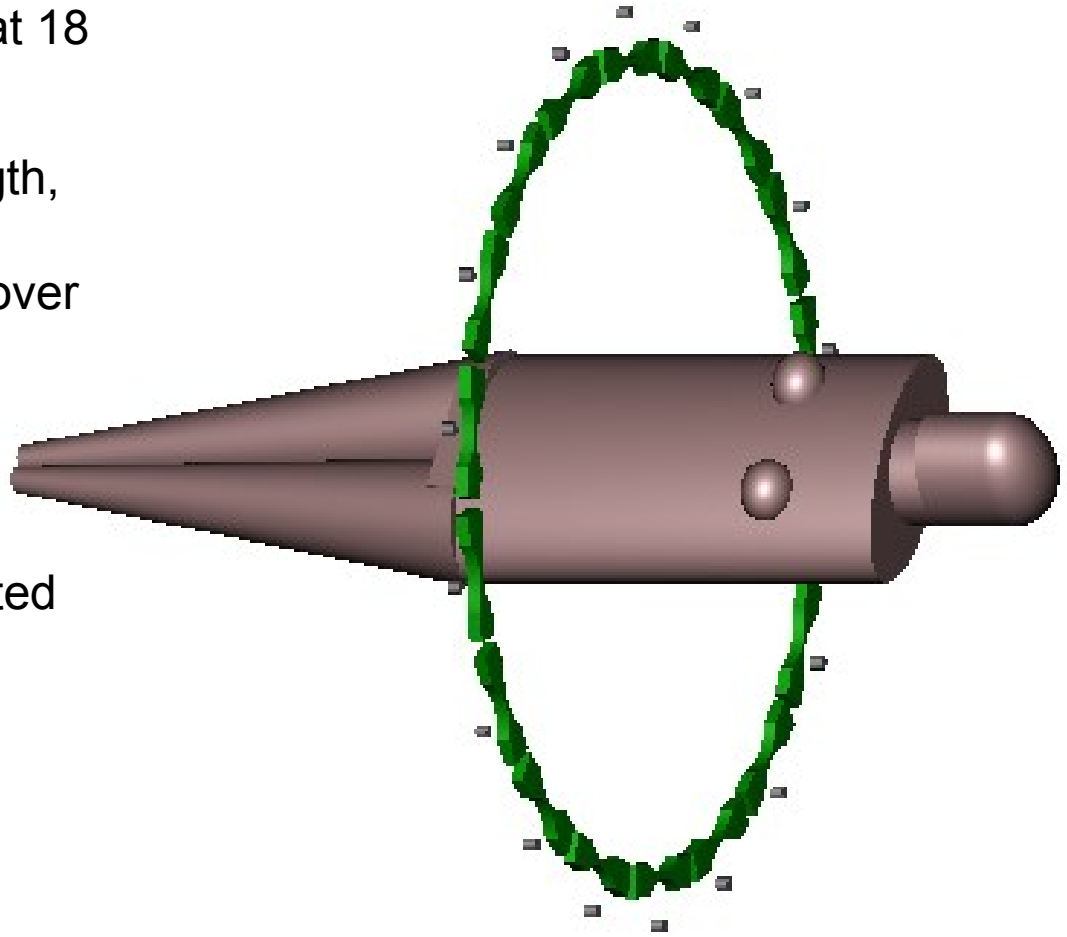
- Source is continuous rotational
- Line sources of 0.5 cm length, emitting photons perpendicular to the line and in a fan angle towards centre of rotation (COR)
- Photon energy from spectra based on W.J. Iles (1987) for tube voltage, filtration and anode angle
- Bow tie filter attenuation based on material, mass attenuation coefficients and path length
- Monte Carlo program is home-made



Public Health England

X-ray Source Model 2: Amjad Khursheed

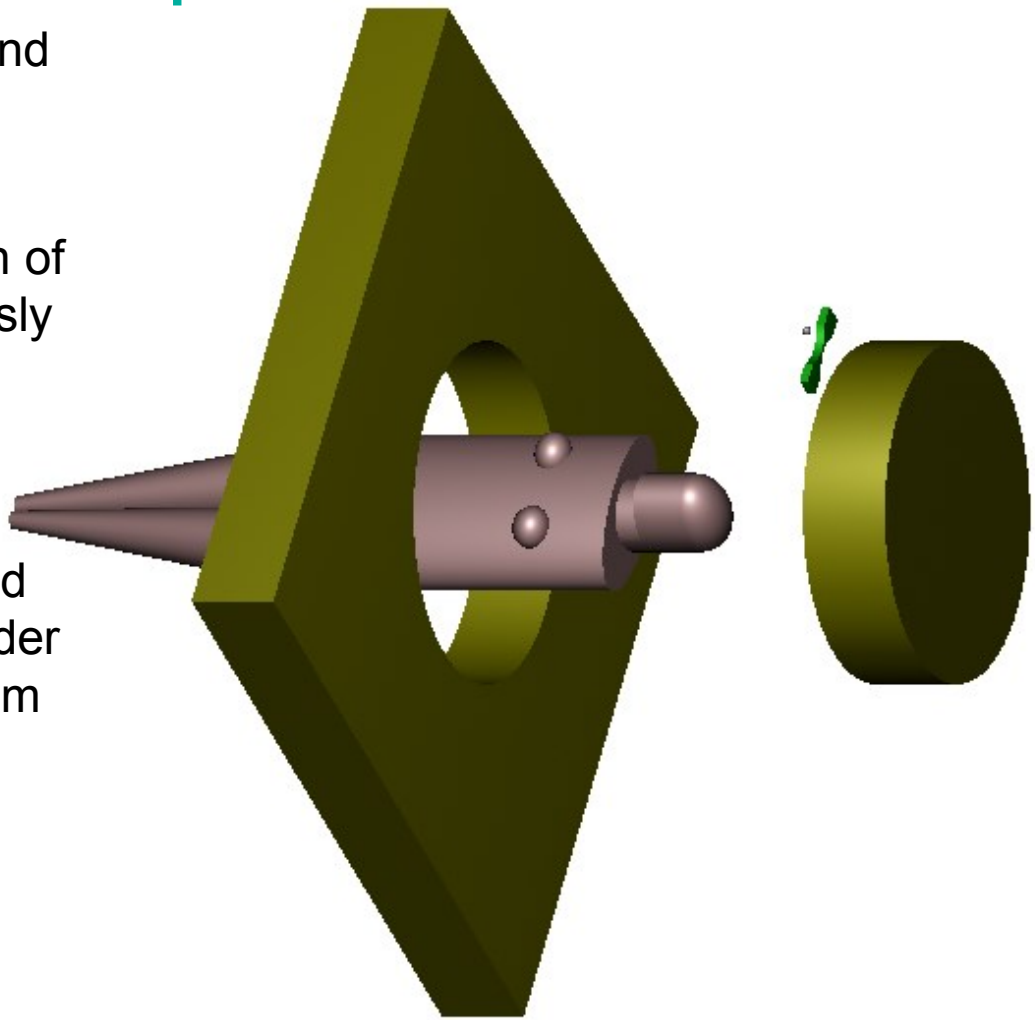
- Line sources are placed at 18 (or 72) discrete positions.
- Line sources of 1 cm length, emitting photons perpendicular to the line over the full fan angle
- Photon energy based on IPEM-78 (1997)
- Bow tie filter is implemented at 18 different places matching the 18 source positions
- Monte Carlo program is MCNP4C



Public Health England

X-ray Source Model 3: MCNP Phase Space File

- CT scanner at a fixed position and write the particles that cross the cylinder.
- Rotate the position and direction of an angle sampled homogeneously between [0, 2π] and write to the second phase space file
- Calculate the anthropomorphic organ doses or CTDI in a second MCNP calculation with the cylinder as a starting particle position from the second phase space file



Public Health England

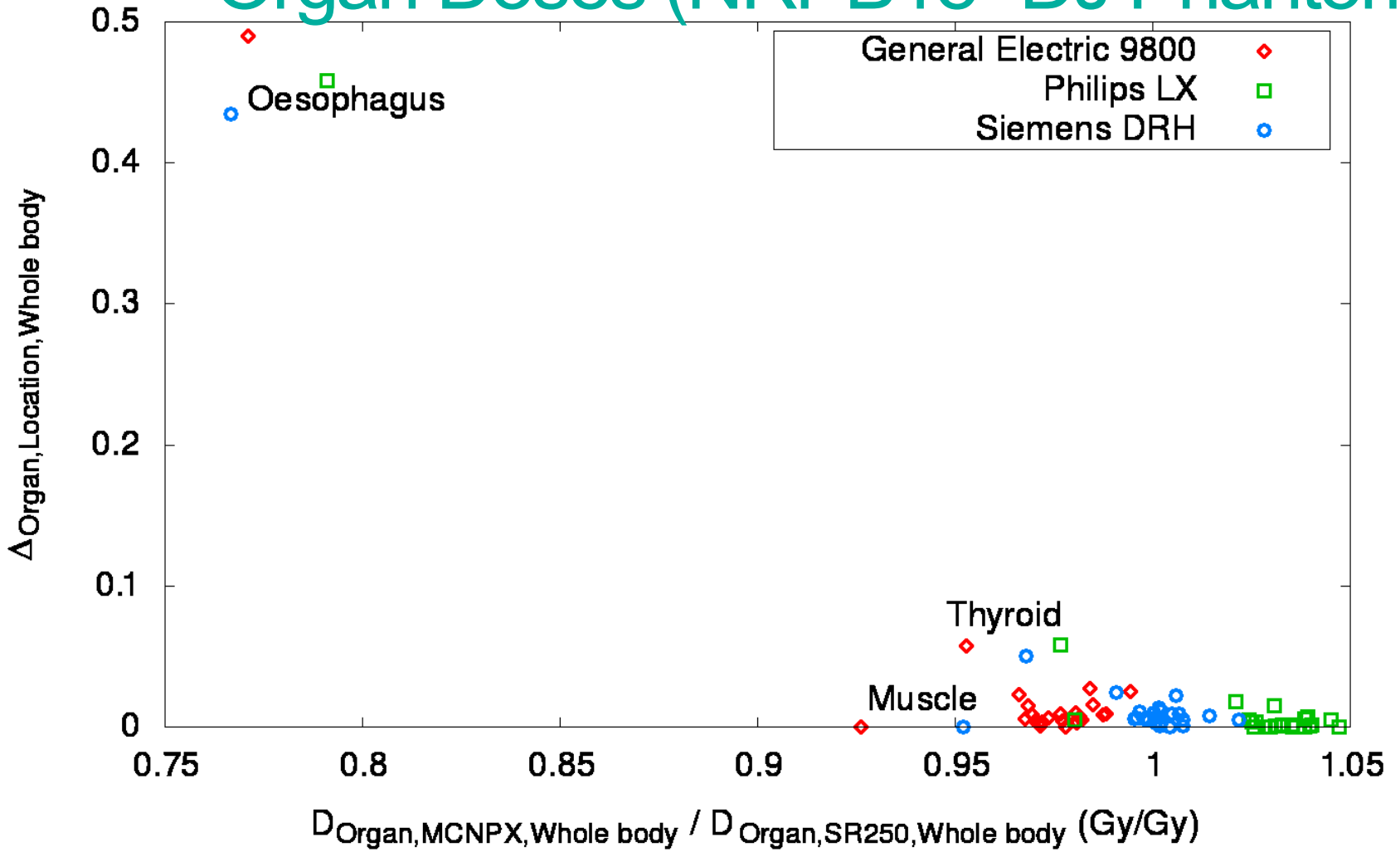
Comparison of Various CT Source Model Simulations

- Philips LX scanner operated at 120 kV
- NRPB18+ anthropomorphic phantom

		Ratios of normalized organ dose per slab		Ratios of E_{60} for whole body exposure
Source	Rotation	Minimum	Maximum	
Line	Continuous	1	1	1
Line	Discrete	0.98	1.03	1.00
Point	Continuous	1.02	1.05	1.03

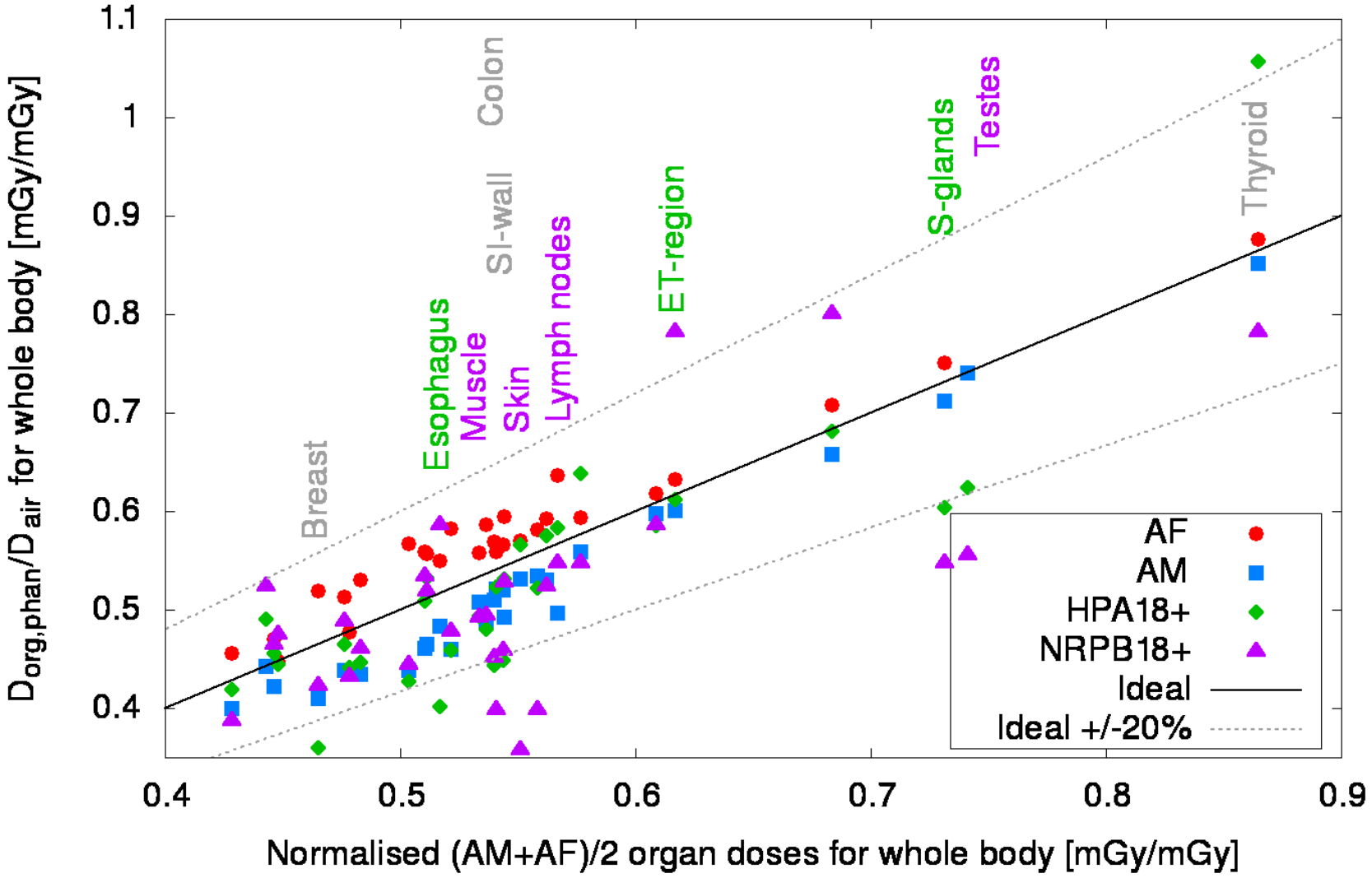
Public Health England

Analysis for 25 Whole Body Normalized Organ Doses (NRPB18+DJ Phantom)



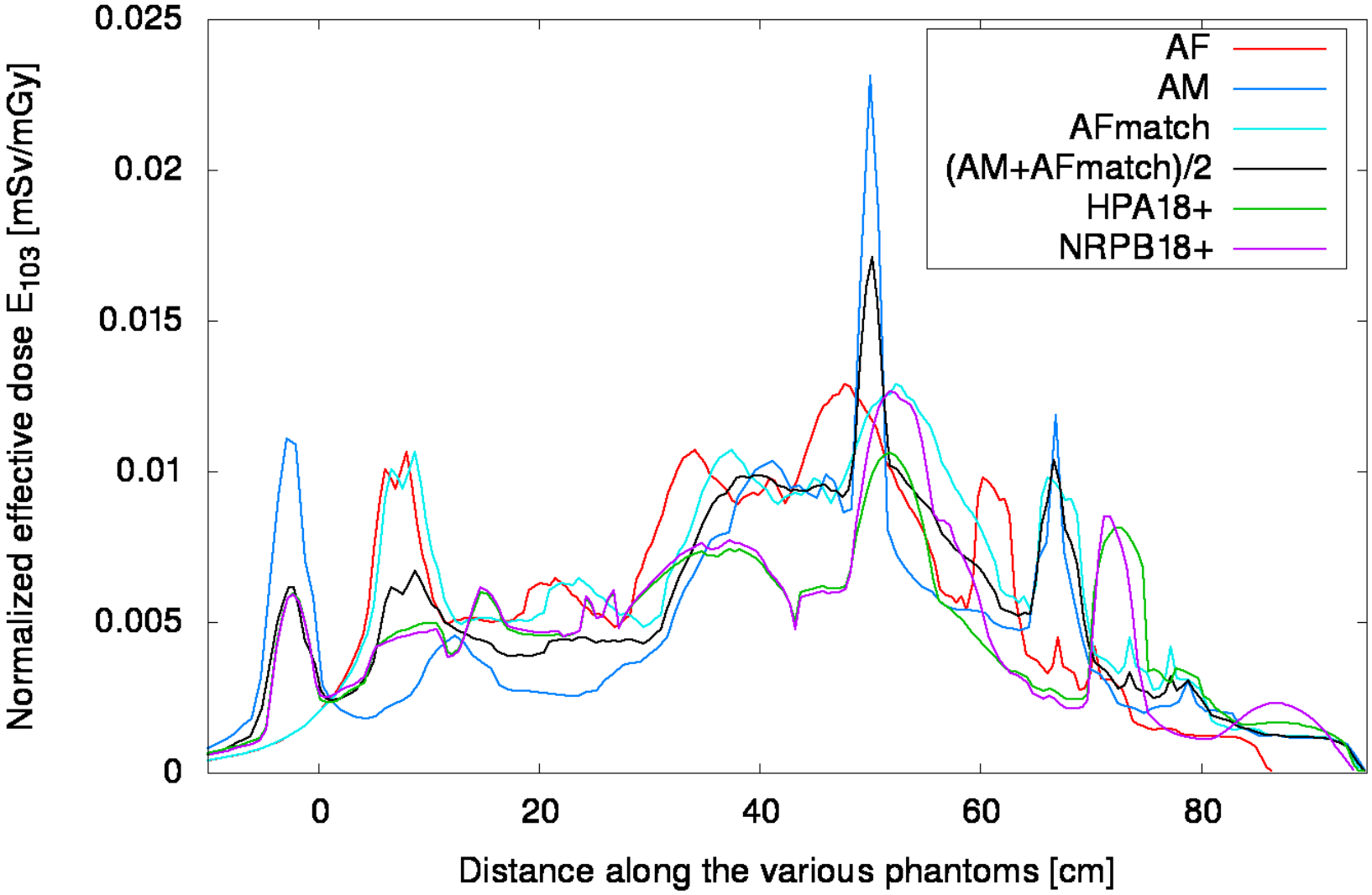
Public Health England

D_{organ}/D_{air} mean of all CT-models



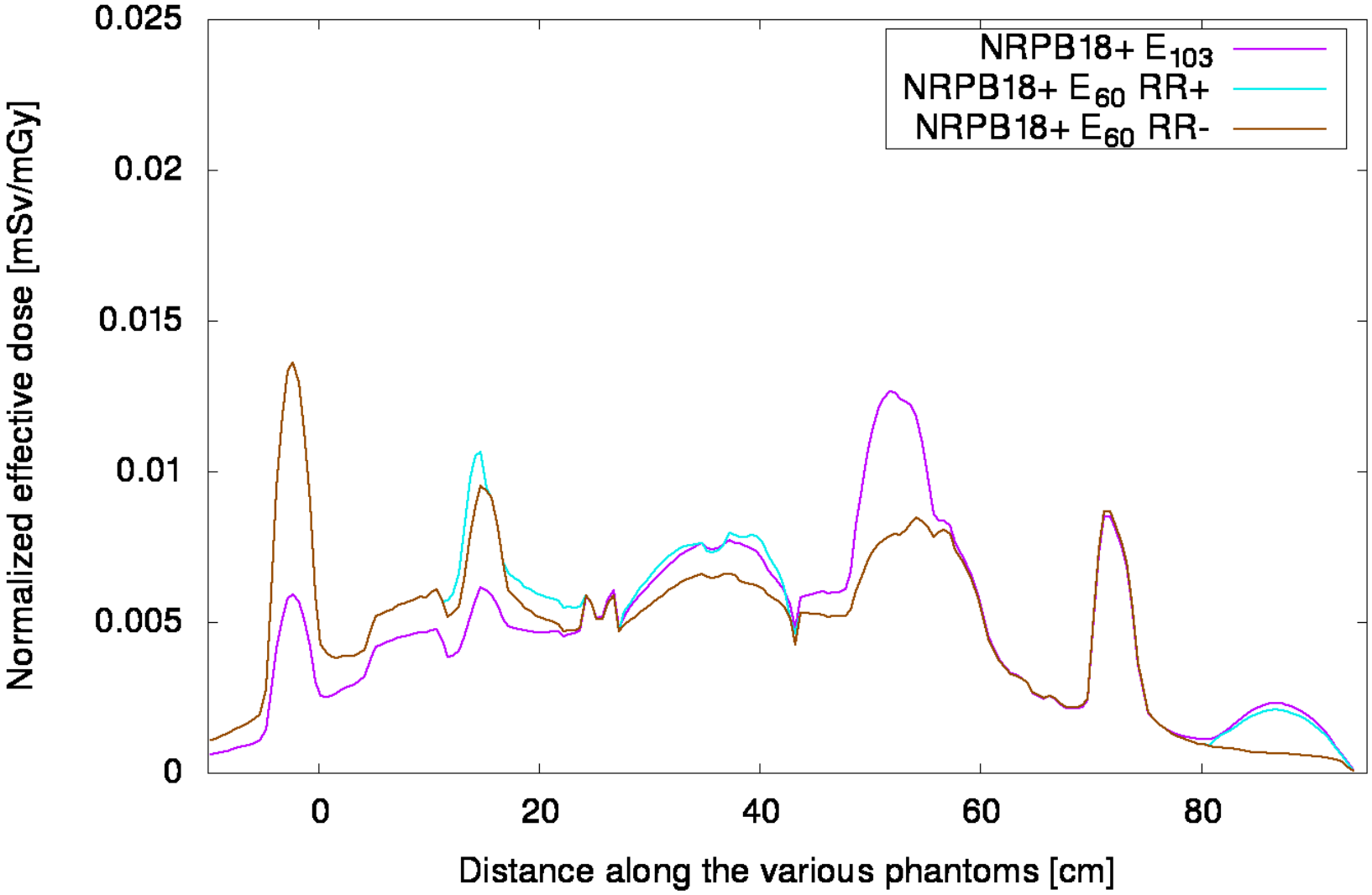
Public Health England

E_{103}/D_{air} mean of all CT-models



Public Health England

E/D_{air} mean of all CT-models



Public Health England

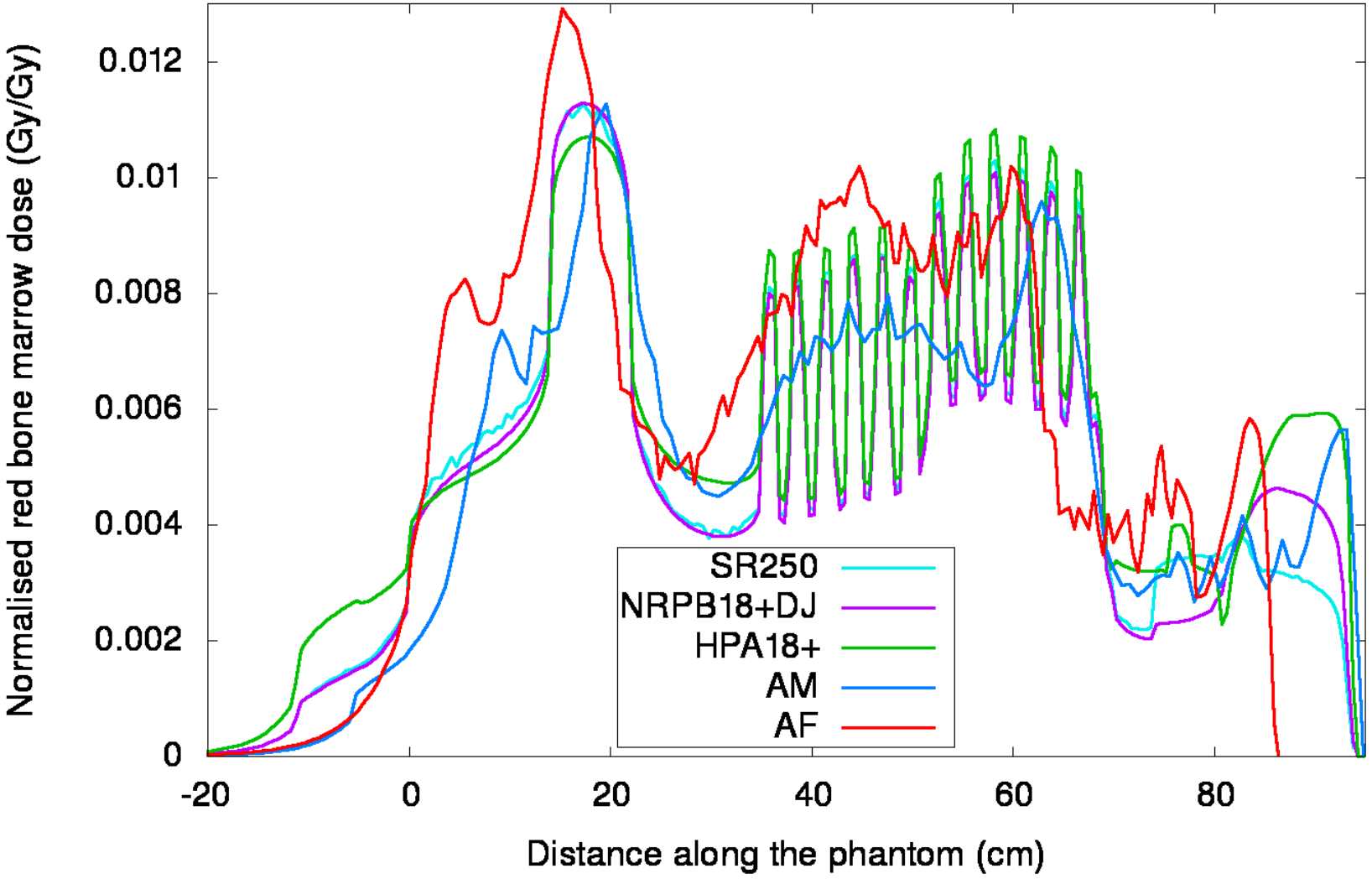
Red bone marrow

Red (active) bone marrow

- Dose to red bone marrow is a leukaemia risk estimator
- Spongeous bone consists of trabecur bone and marrow cavities, with sizes in the order of tens to thousands of micrometre
- NRPB-SR250: stylised phantom, homogeneous bones, Cristy distribution adjusted by Eckerman, and King & Spiers dose enhancement (Cord-length estimation)
- NRPB18+DJ: Quality Assurance of NRPB-SR250
- HPA18+: Further development of the NRPB18+ phantom for additional risk and remainder organs
- AM and AF: voxel phantoms, bones consists of compact bone, spongeous bone, medullary cavity and cartilage, ICRP-110 distribution based on Cristy, and Johnson et al. (ICRP-116) dose enhancement (Micro CT images)

Public Health England

Red bone marrow dose
Siemens Somatom DRH at 125 kV



Public Health England

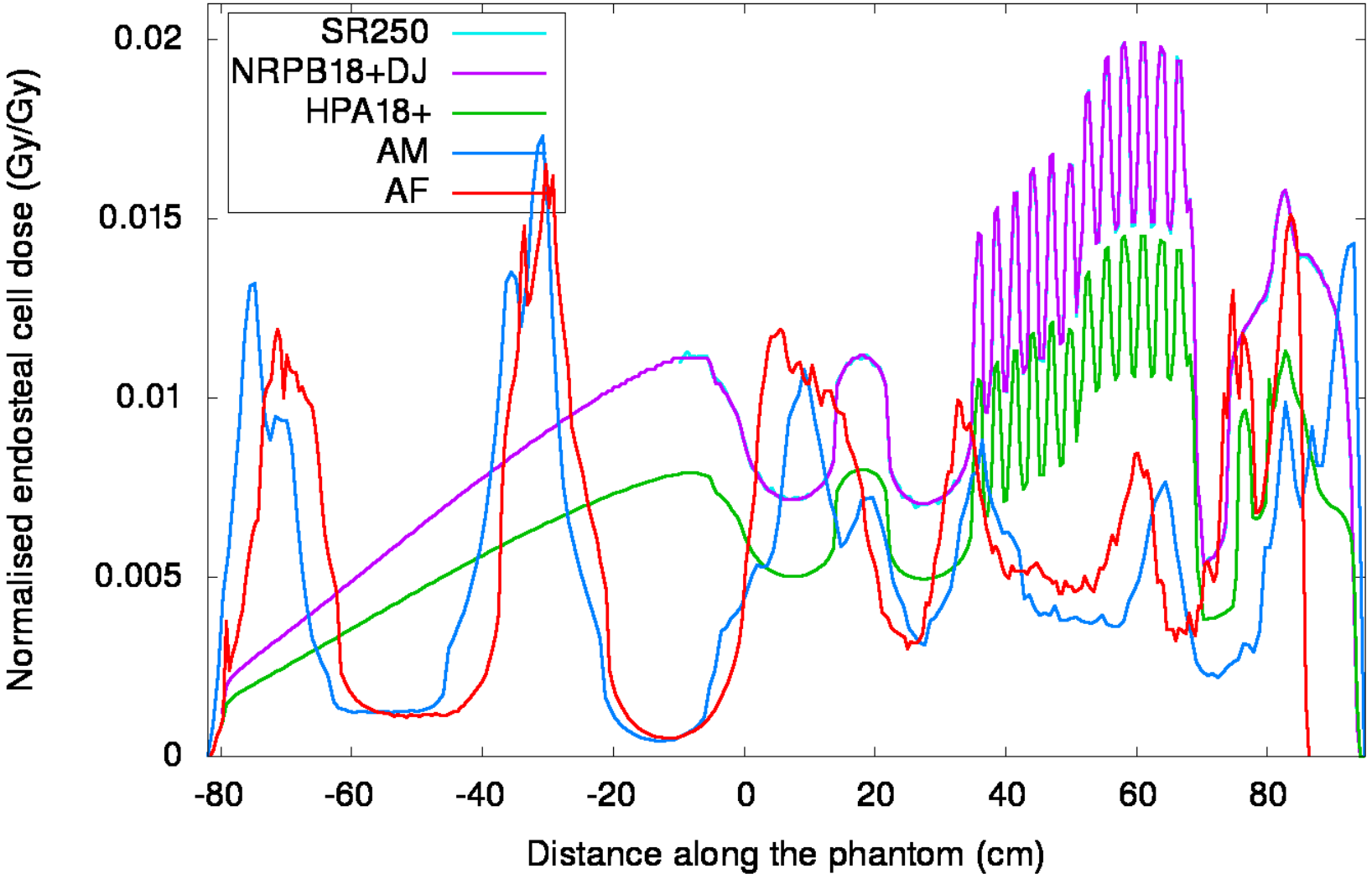
Endosteal cells (Bone surface)

Endosteal cells or bone surface

- Dose to endosteal cells is a bone cancer risk estimator
- Bone consists of an outside compact bone layer and an internal medullary cavity and spongeous bone, which consists of trabecular bone and marrow cavities
- Endosteal cells have the local red and yellow marrow mixture composition
- NRPB-SR250: stylised phantom, homogeneous bones, the skeleton dose is used as over-estimator for endosteal cell dose
- NRPB18+DJ: Quality Assurance of NRPB-SR250
- HPA18+: Further development of the NRPB18+ phantom, mass weighted endosteal cell distribution, soft tissue dose with Wall et al. dose enhancement based on 10 micrometre distance range from hard-bone
- AM and AF: voxel phantoms, ICRP-110 distribution, and Johnson et al. (ICRP-116) dose enhancement (Micro CT images) based on 50 micrometre

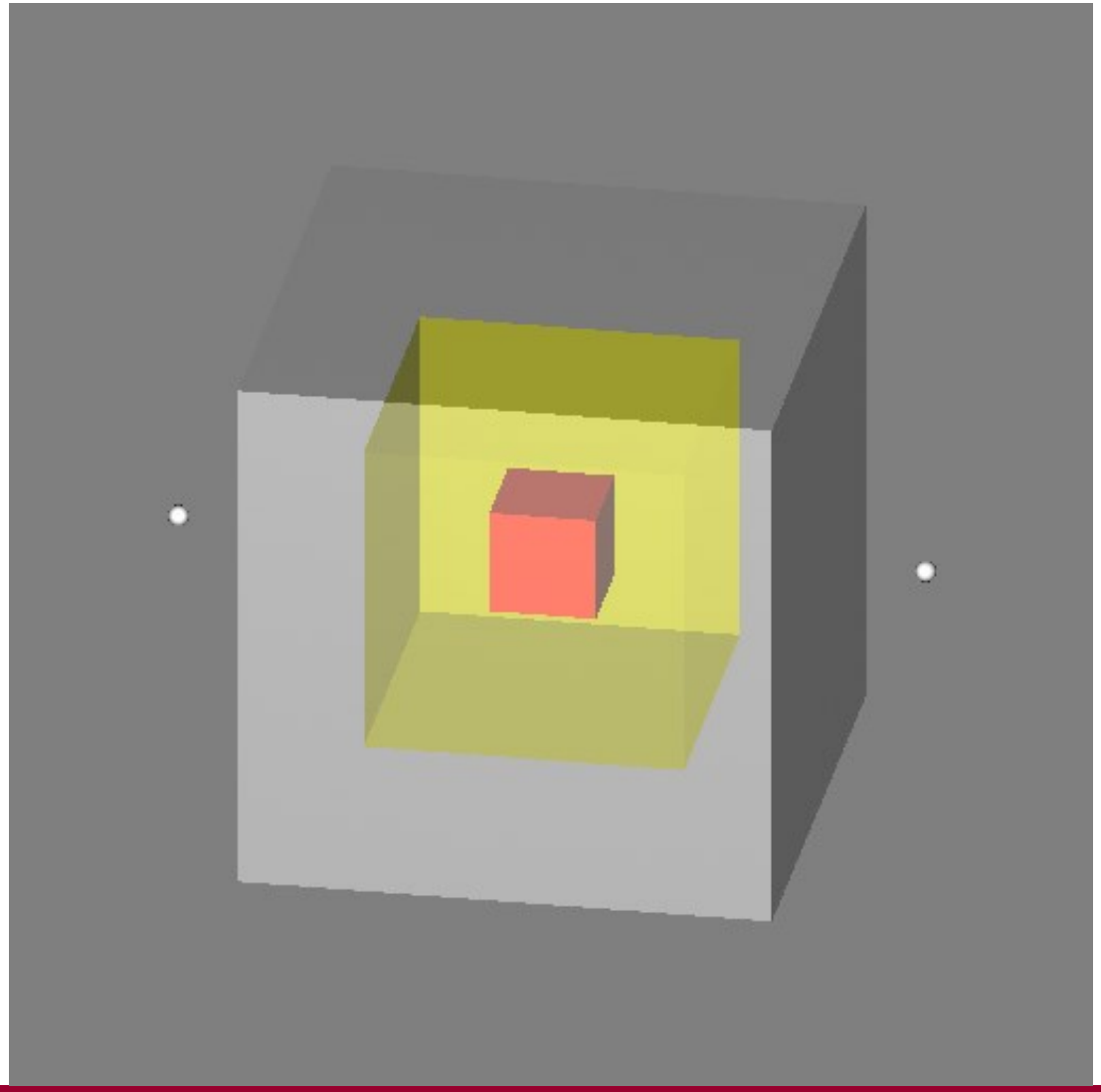
Public Health England

Endosteal cell dose
Siemens Somatom DRH at 125 kV



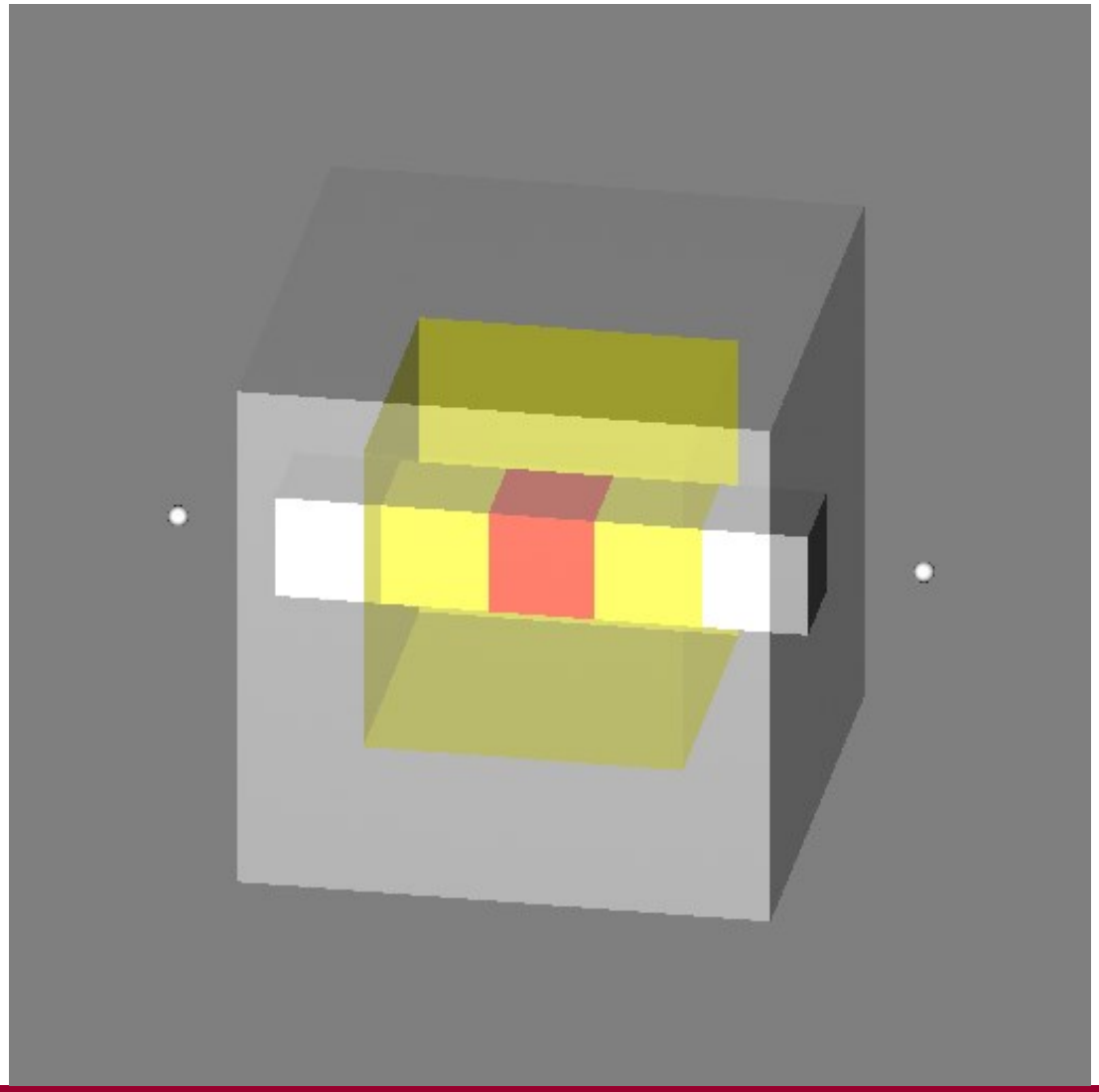
Public Health England

5x5x5 lattice with 2 sources



Public Health England

5x5x5 lattice with 2 sources



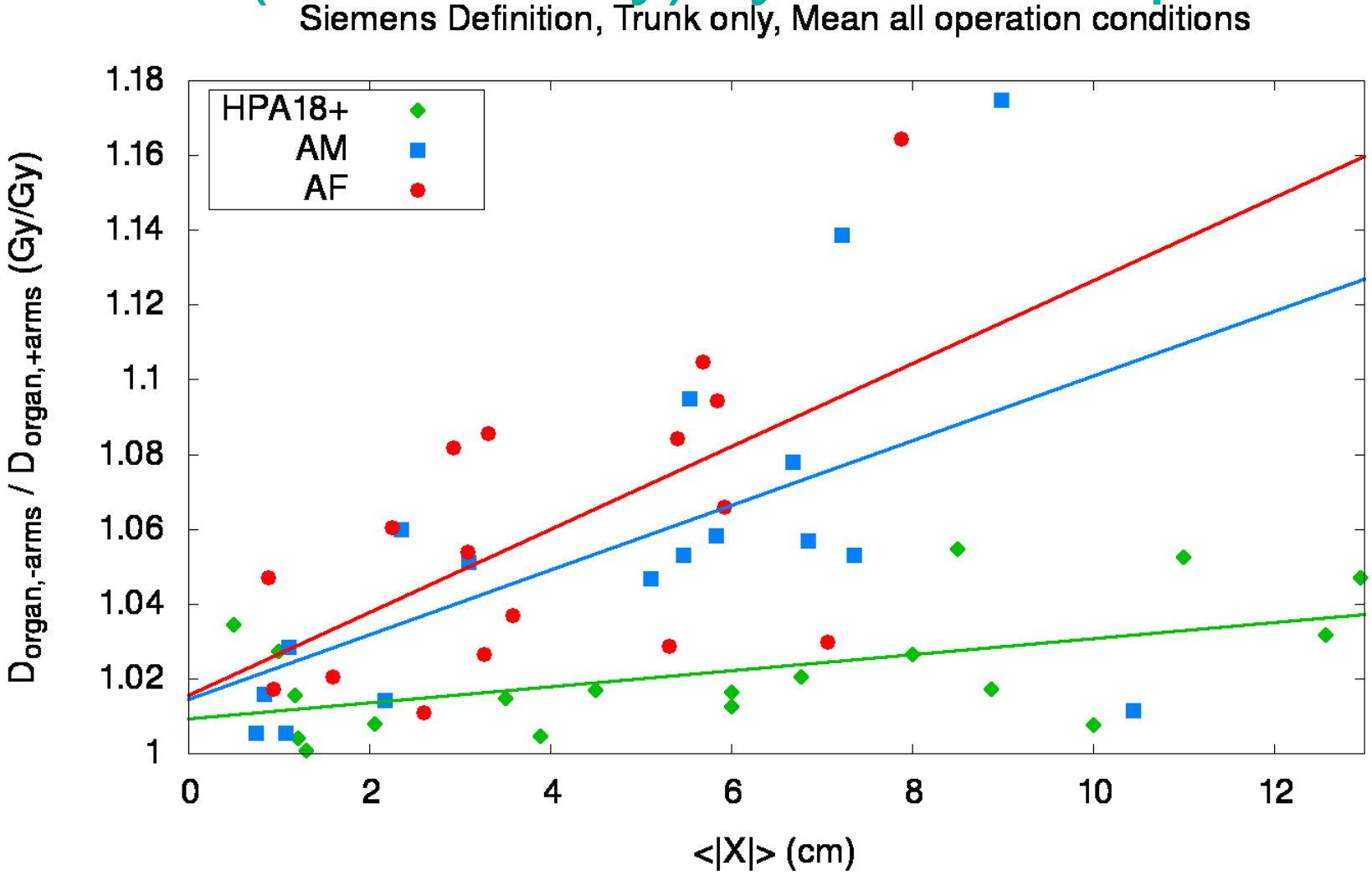
5x5x5 lattice MCNP surface tally

Public Health England

MCNP tally surface Specification	Void Right Source Fluence (cm^{-2})	RelErr	Void Left Source Fluence (cm^{-2})	RelErr	Void Theory Fluence (cm^{-2})	Signific. Fluence
(101 < 2[2 0 0] < 1)	0.000E+00	0.000	0.000E+00	0.000	6.8754E-02	-
(101 < 2[1 0 0] < 1)	0.000E+00	0.000	1.913E-02	0.007	1.9111E-02	0.16
(101 < 2[0 0 0] < 1)	0.000E+00	0.000	8.597E-03	0.011	8.6823E-03	-0.90
(101 < 2[-1 0 0] < 1)	0.000E+00	0.000	4.789E-03	0.015	4.9225E-03	-1.87
(101 < 2[-2 0 0] < 1)	0.000E+00	0.000	3.019E-03	0.018	3.1621E-03	-2.49
(102 < 2[2 0 0] < 1)	3.222E-03	0.018	0.000E+00	0.000	3.1621E-03	1.08
(102 < 2[1 0 0] < 1)	5.002E-03	0.014	0.000E+00	0.000	4.9225E-03	1.14
(102 < 2[0 0 0] < 1)	8.780E-03	0.011	0.000E+00	0.000	8.6823E-03	1.06
(102 < 2[-1 0 0] < 1)	1.932E-02	0.007	0.000E+00	0.000	1.9111E-02	1.48
(102 < 2[-2 0 0] < 1)	0.000E+00	0.000	0.000E+00	0.000	6.8754E-02	-

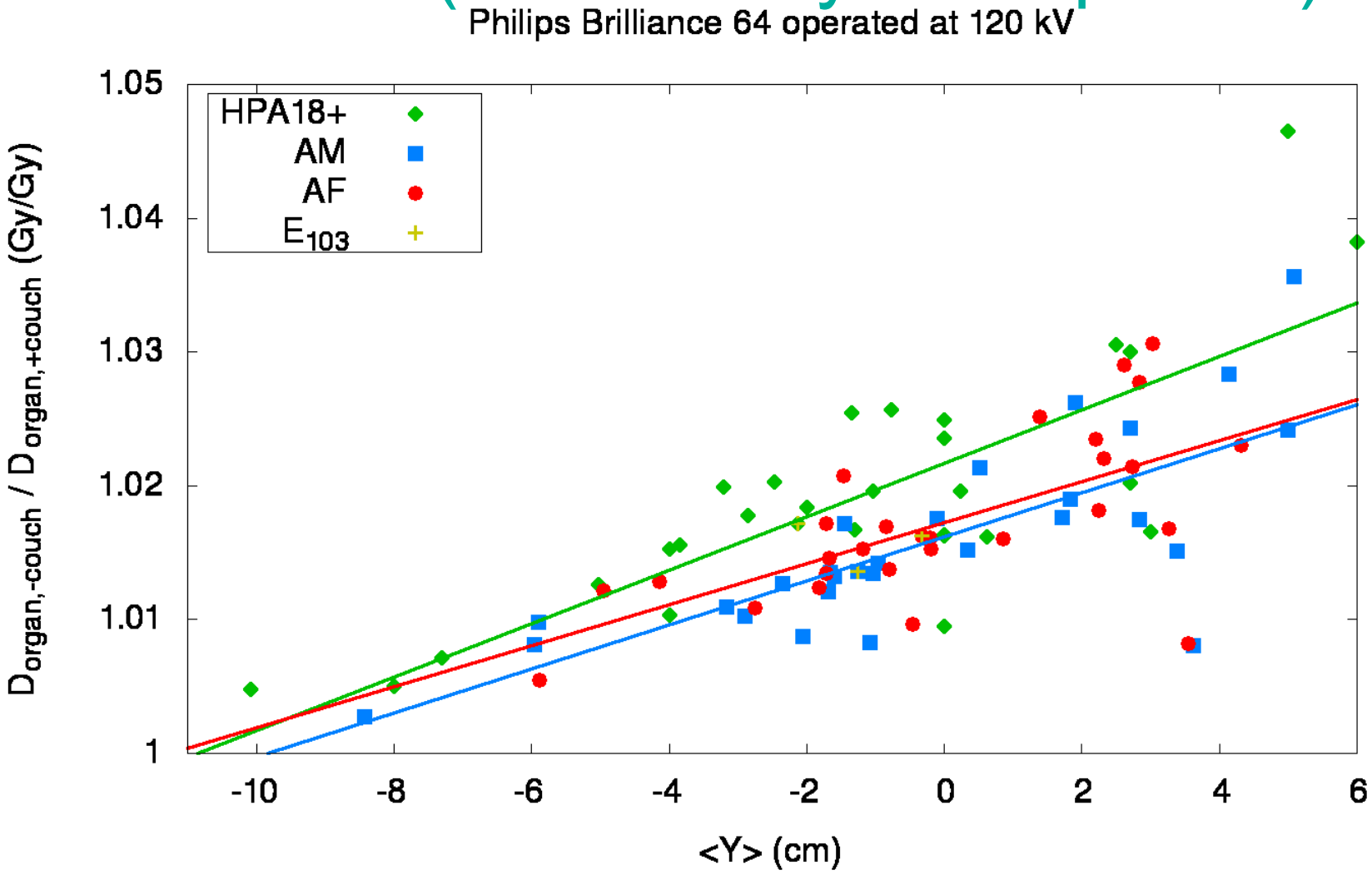
Public Health England

Influence of Arms on Organ Dose (Whole Body) by Lateral Displacement



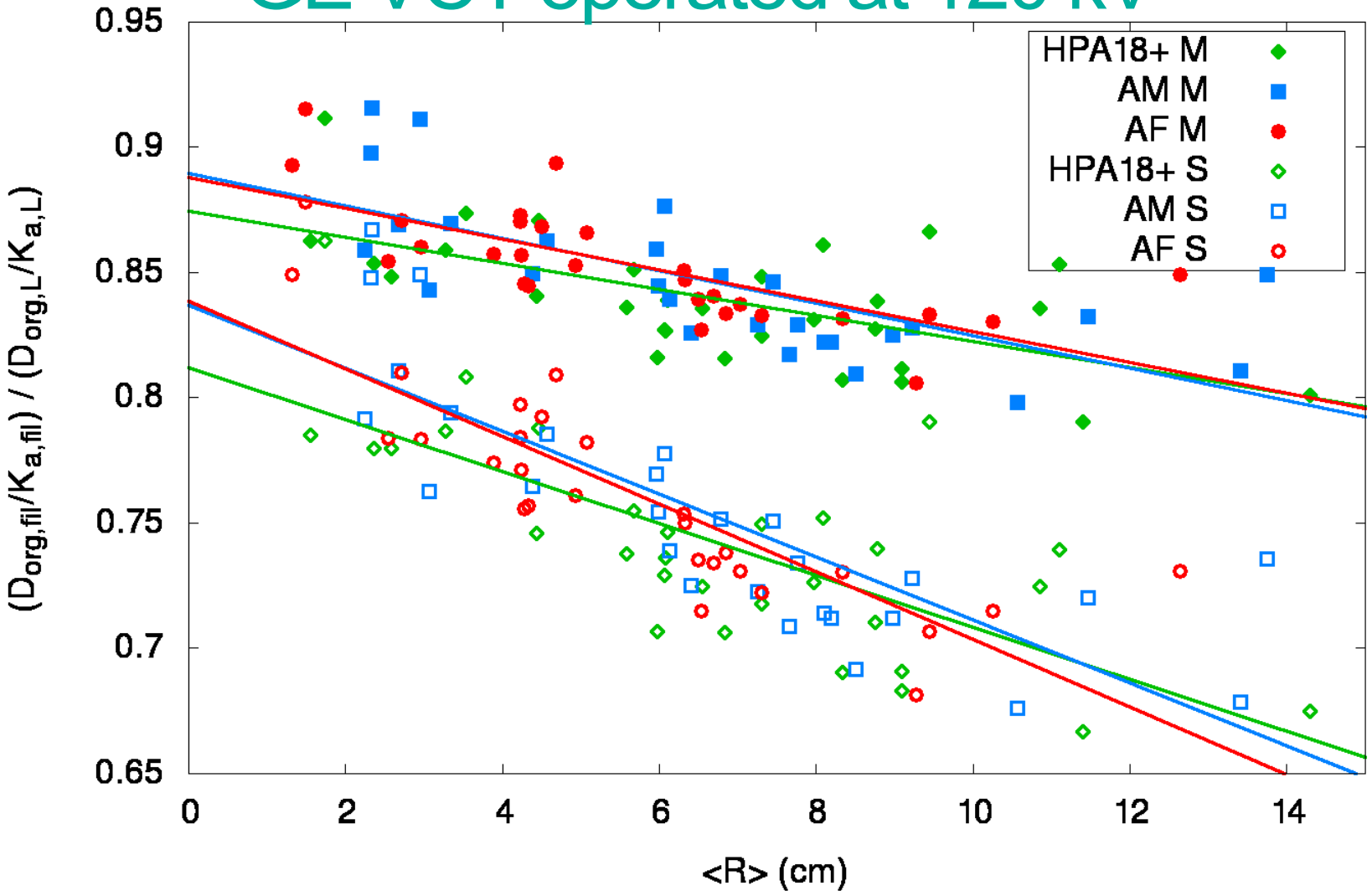
Public Health England

Influence of the Couch on Organ Dose (Whole Body CT Exposure)



Public Health England

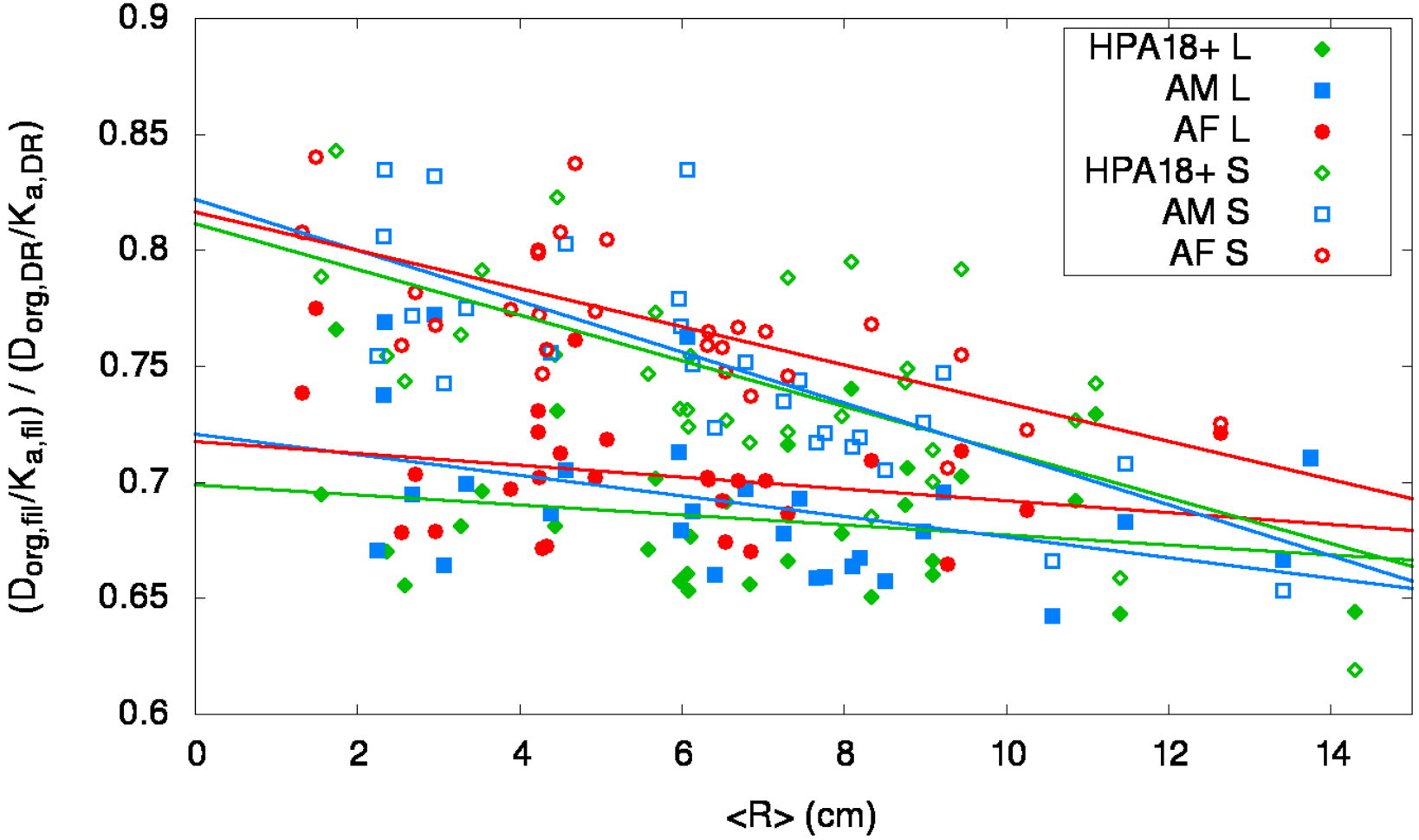
Influence of bow-tie filter for the GE VCT operated at 120 kV



Public Health England

Influence of Bow-tie Filter on Organ Dose (Whole Body) by Radial Position

Toshiba Aquilion 16 operated at 120 kV



Public Health England

Conclusion

- The calculation times show big differences between MCNP5 and MCNPX, less difference for the hardware (frequency) and for the compiler
- Whole body organ doses (SR250) can be reproduced within 5%.
- Whole body organ doses mostly within 20% for the 4 phantoms.
- Red bone marrow dose from dose enhancement factor King & Spiers to Johnson et al.
- Endosteal cell dose from average bone dose to defined in compartments with a dose enhancement factor.
- Lattice surfaces need to be doubled to count correctly.
- Influence of arms on trunk organ doses show a lateral displacement dependency.
- Influence of the couch on organ doses show a height dependency.
- Influence of bow-tie filters on organ doses show normally a radius dependency.

Public Health England

Future work

- Look at generic CT scanners
- Make the organ dose conversion coefficients available for medical physicists
- Calculate the normalised organ dose conversion coefficients for the paediatric phantoms

Public Health England

Thank you for your attention