



The Clatterbridge  
Cancer Centre  
NHS Foundation Trust

# Patient-Specific Monte Carlo Simulation and Effective Dose Calculation for Chest Computed Tomography Using a Hybrid Phantom

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Clatterbridge Cancer Centre*

# Presentation Overview

## 1. Introduction

1. Project rationale and background
2. Monte Carlo introduction
3. Project objectives



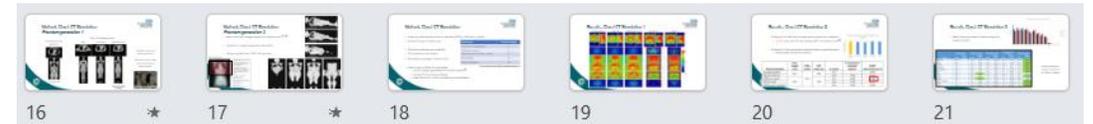
## 2. CT Monte Carlo model generation, calibration, and validation

1. Method
2. Results



## 3. Chest CT simulation and phantom intercomparison

1. Method
2. Results



## 4. Conclusions and further work



# Project Introduction 1

- Third of three journal-style papers in my HSST project
- Striving for as accurate a dose distribution as possible in CT patients
  - Knowledge generation in scientific community
  - Improve justification process?
  - Build a foundation for further research
  - In the future, could personalised risk estimation be a possibility?

We can't get anywhere close to this at the moment, but will assume there will be advances in epidemiology, genetics, and radiobiology.

An accurate 3D dose distribution is likely the most future-proof dosimetric output.



# Project Introduction 2

- There are lots of CT dosimetry tools available

[1] ImPACT

Organ	w <sub>1</sub>	H <sub>1</sub> (mSv)	w <sub>2</sub> H <sub>2</sub>
Stomach	0.08	2.1	0.04
Bone Marrow	0.12	3.9	1.2
Colon	0.17	11	1.6
Lung	0.12	16	1.9
Stomach	0.12	15	1.8
Bladder	0.04	15	0.6
Heart	0.12	12	1.5
Choroid plexus (Thyroid)	0.04	18	0.71
Thyroid	0.04	4.7	0.19
Skin	0.01	7.1	0.071
Brain Surface	0.01	15	0.15
Brain	0.01	0.17	0.0017
Salivary Glands (Cran)	0.01	0.17	0.0017
Removable	0.12	12	1.5
Not Applicable	0	0	0
<b>Total Effective Dose (mSv)</b>			<b>12</b>

[2] CT-Expo

[3] WAZA-ARI

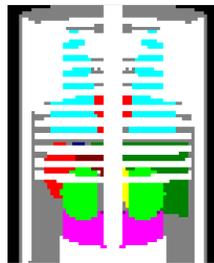
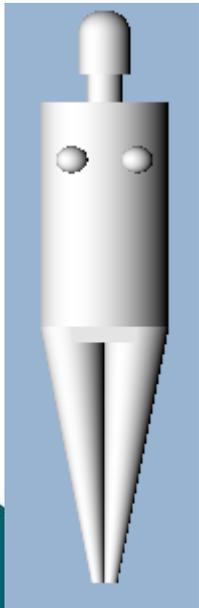
[4] Virtual Dose

[5] NCICT

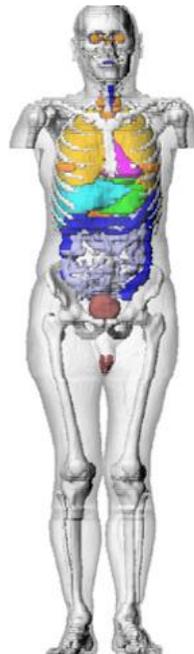
# Project Introduction 3

- An accurate dose distribution depends on a few things:
  - Realistic representation of the patient
  - Dose calculation method
  - Beam model

Dose-point kernel  
Analytic approach  
Monte Carlo simulation  
AI?



Phantom  
images taken  
from [6]

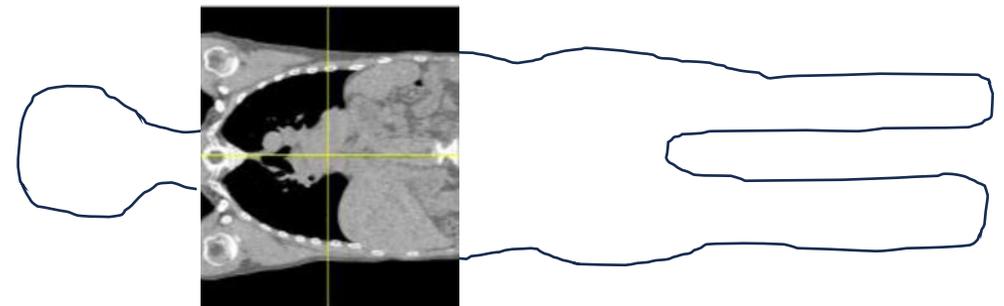


Screengrab from [5]



# Project Introduction 4

- Beam model and calculation method well established for Monte Carlo
  - Assess the accuracy of the method in the validation stage
- How can we maximise realism/accuracy for our patient/phantom?
  - Use patient images as far as possible
  - Fill in the blanks?
  - Kalender et al did similar with phantoms only<sup>[7]</sup>



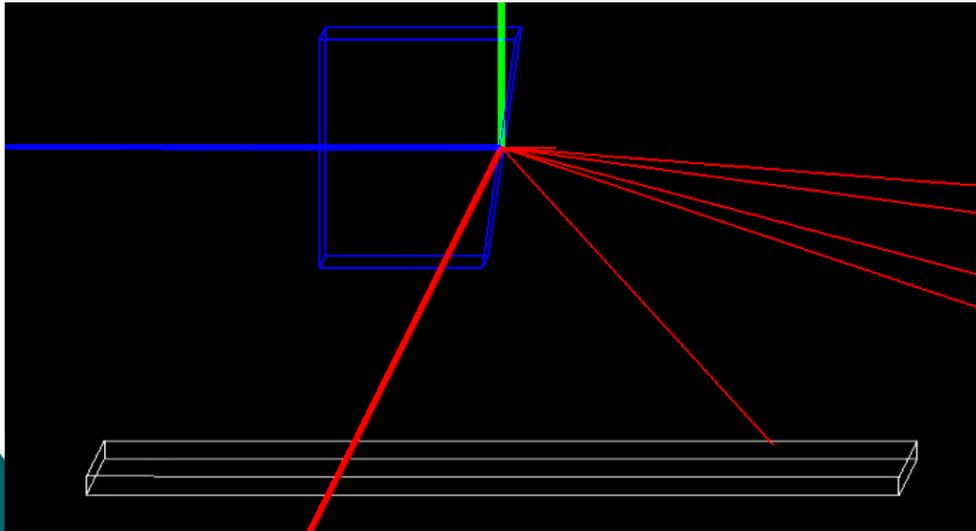
# Monte Carlo: An introduction

- I used GATE, the **GEANT4 Application for Tomographic Emission**<sup>[7]</sup>
  - Uses macro language with a built-in interpreter
  - I used GATE V9.0 which runs in Linux
  - 4 servers + 1 research computer, each running virtual machines
- Define a 'world' and daughter volumes within it
- Define a source and choose a physics list, and simulation parameters
- Attach 'Actors' to volumes to generate outputs
  - Dose, incident energy spectrum etc.
- Simulate N primary particles generated by the source

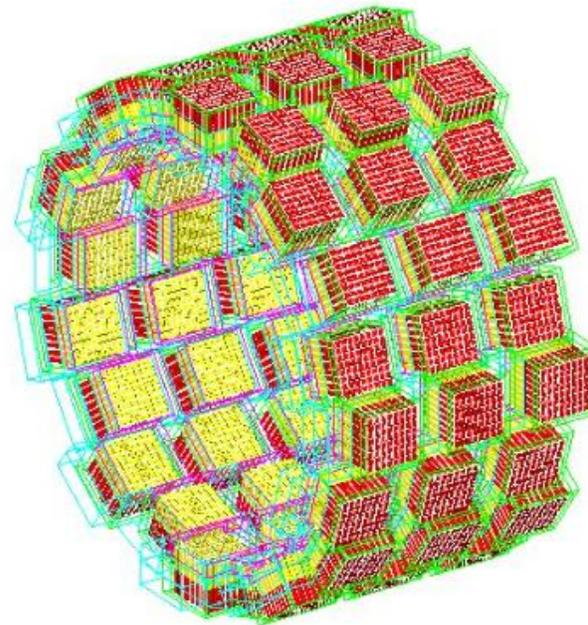


# GATE: An Introduction

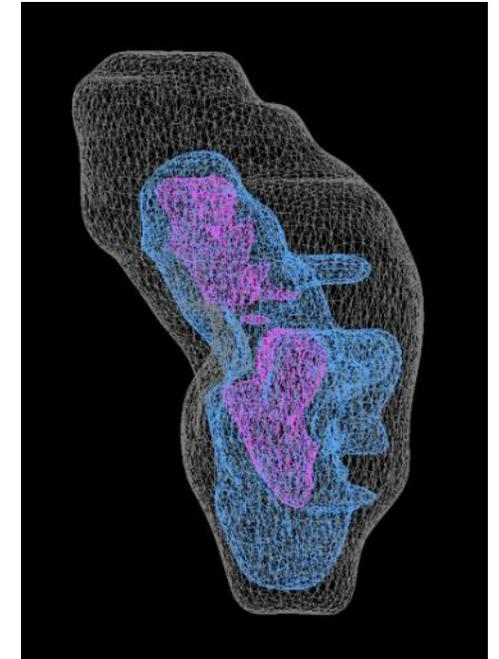
- Define or import volumes to build a geometry



A simple geometry modelling a planar x-ray tube



A PET scanner crystal array using a ring repeater<sup>[8]</sup>

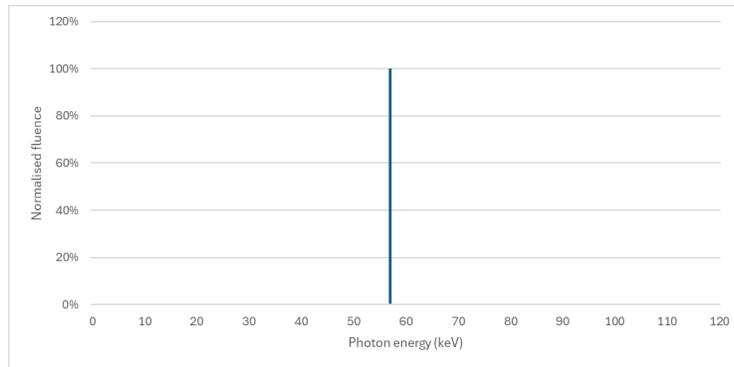


A model of a kidney (tessellated volume) imported into GATE<sup>[8]</sup>

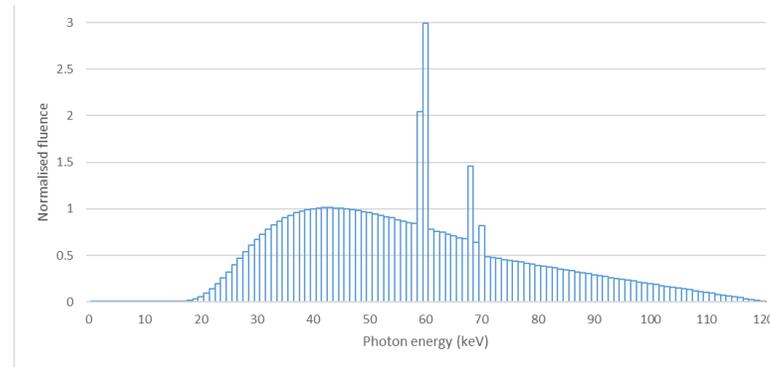


# GATE: An Introduction

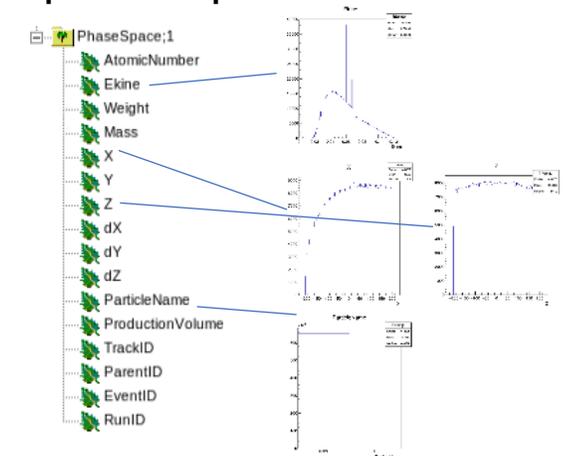
- Define a source energy distribution:
  - Mono-energetic



histogram



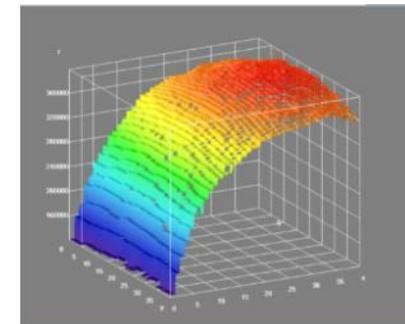
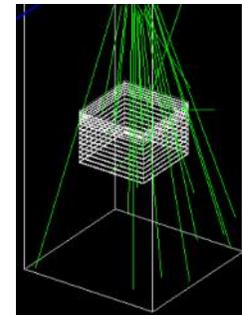
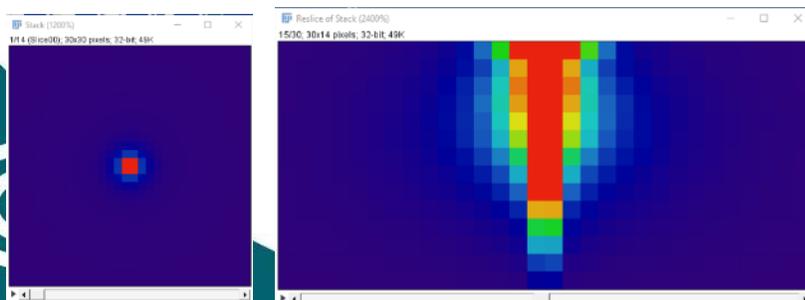
phase space



- Define a source geometry:
  - Pencil

Shape & solid-angle ( $\phi, \theta$ )

other (e.g. phase space)



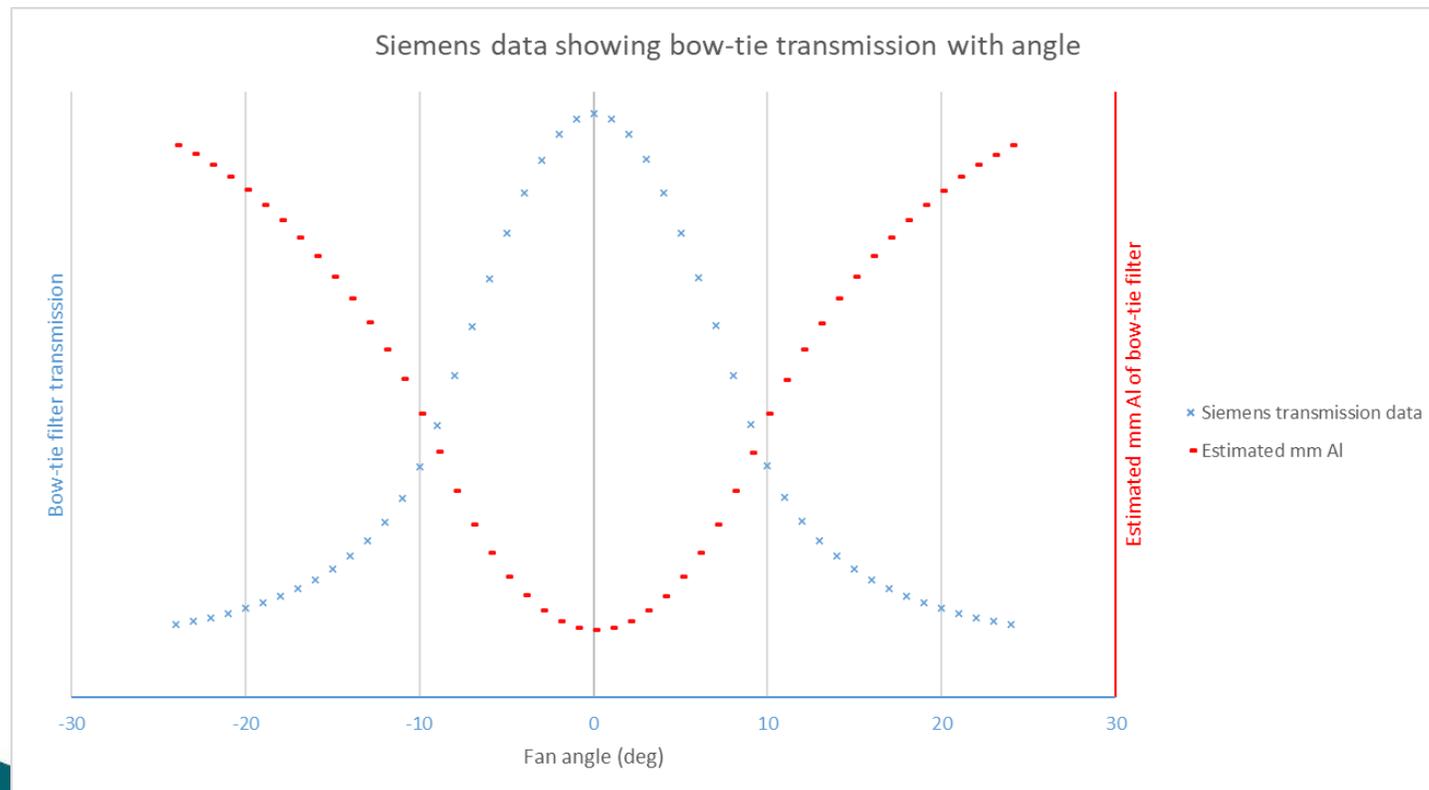
# Project Objectives

- Monte Carlo model of a CT scanner
  - Generate model
  - Calibrate
  - Validate → Consider validated if  $CTDI_w < 10\%$  diff (arbitrary tolerance)
- Generate a hybrid phantom
- Simulate a simple chest CT with various phantoms and compare calculated organ and effective doses
  - Real patient data
  - Hybrid
  - ICRP110<sup>[9]</sup>
  - Modified ICRP110



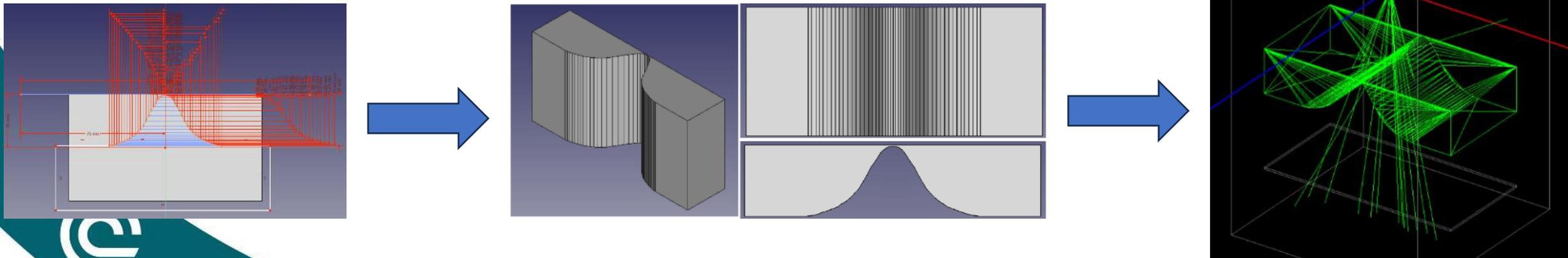
# Method – CT Model Generation

- Data kindly provided by Siemens<sup>[9]</sup> RE bow-tie geometry and material
  - % transmission vs emission angle
  - Converted to estimated mm thickness using central HVL measurement + IPEM report 78 <sup>[11]</sup>



## Method – CT Model Generation

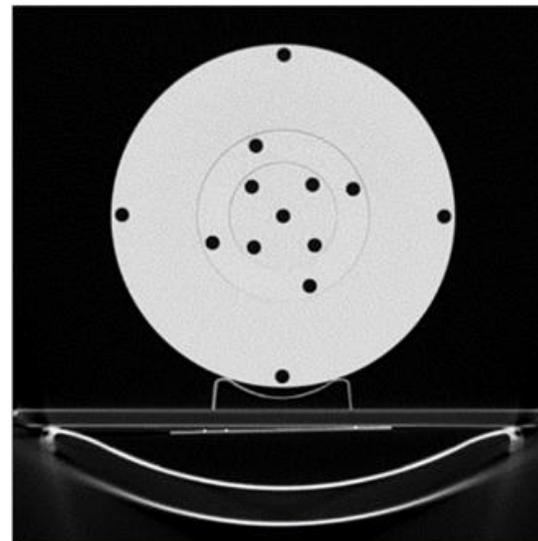
- Used CAD<sup>[11]</sup> to build a model of the bow-tie
- Exported the model as a .stl file
- Imported the file into a GATE simulation to transmit a 120 kVp, 8 mm Al histogram source through
- Define an object with a phase space actor attached to capture transmission
  - Output a library of particle trajectories and energies



I actually had to go through 2 BT iterations to tailor this to our local measurements.

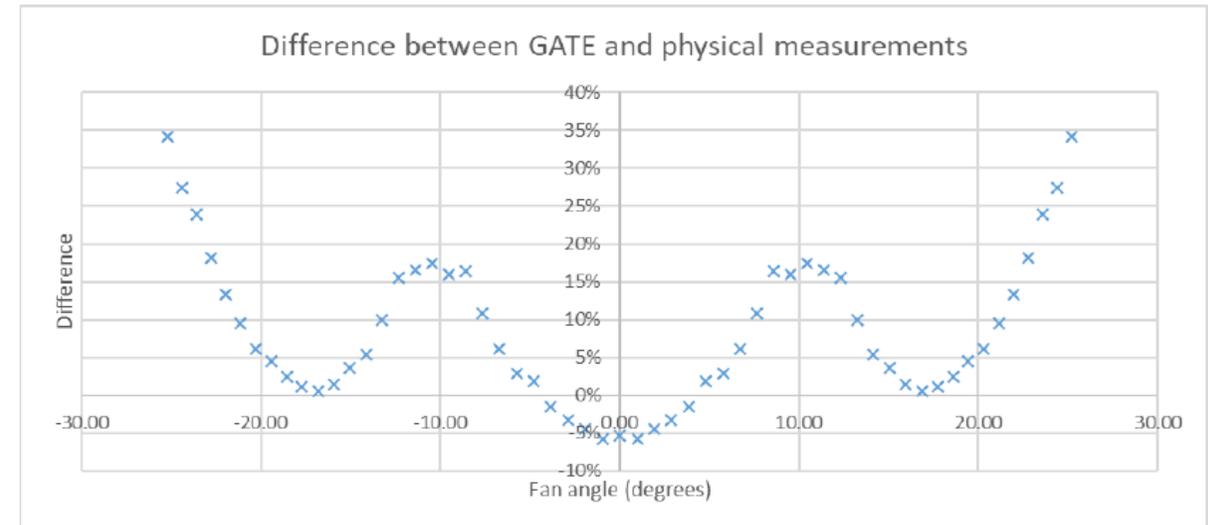
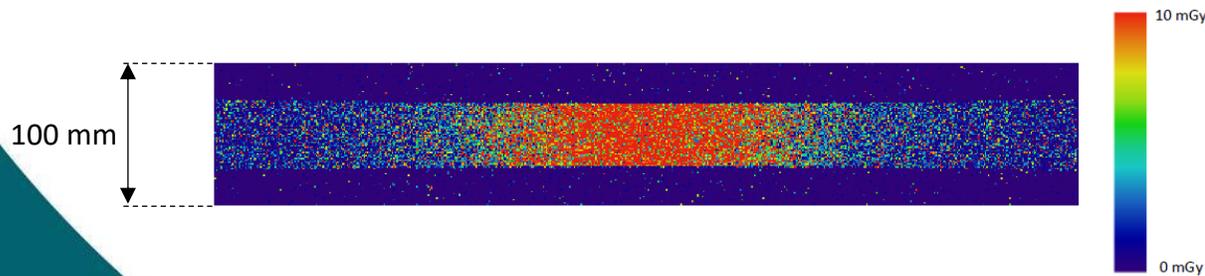
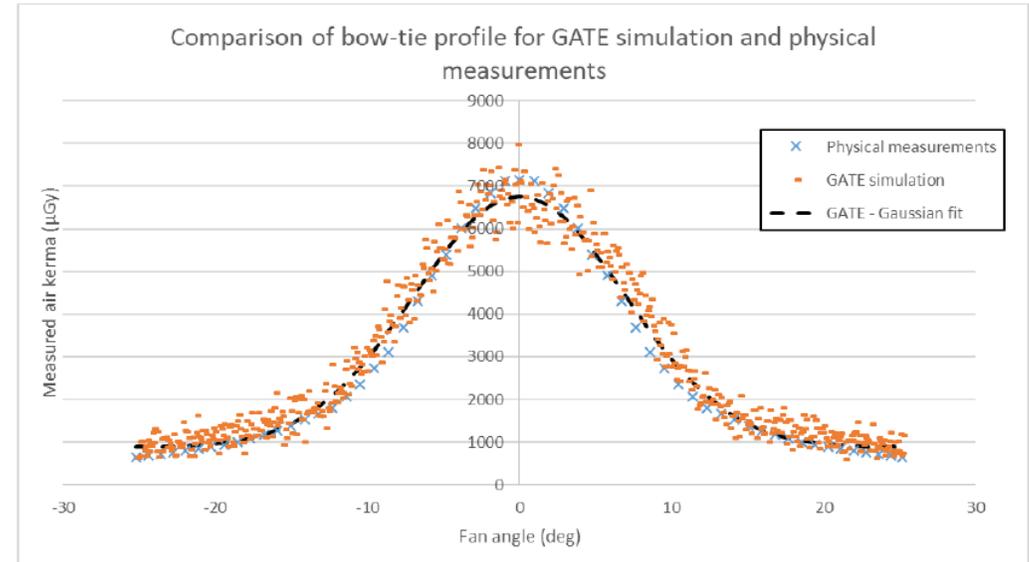
## Method – CT Model Generation

- Used the phase space file as a source definition
  - 1 simulation for each of 120 projections
- Scanned a CTDI phantom and imported the data into a GATE sim
- Compare simulated CTDI vacant slot doses against physical chamber measurements



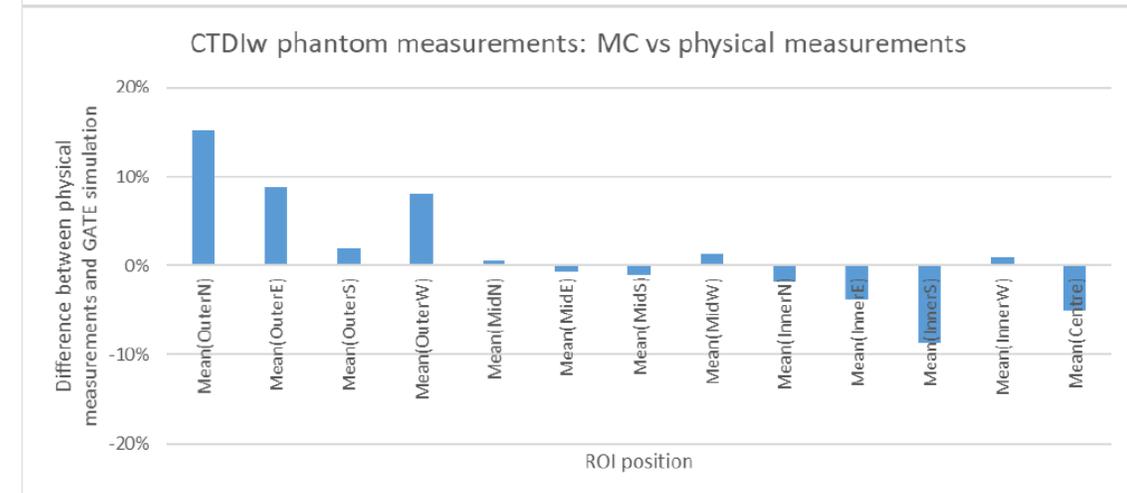
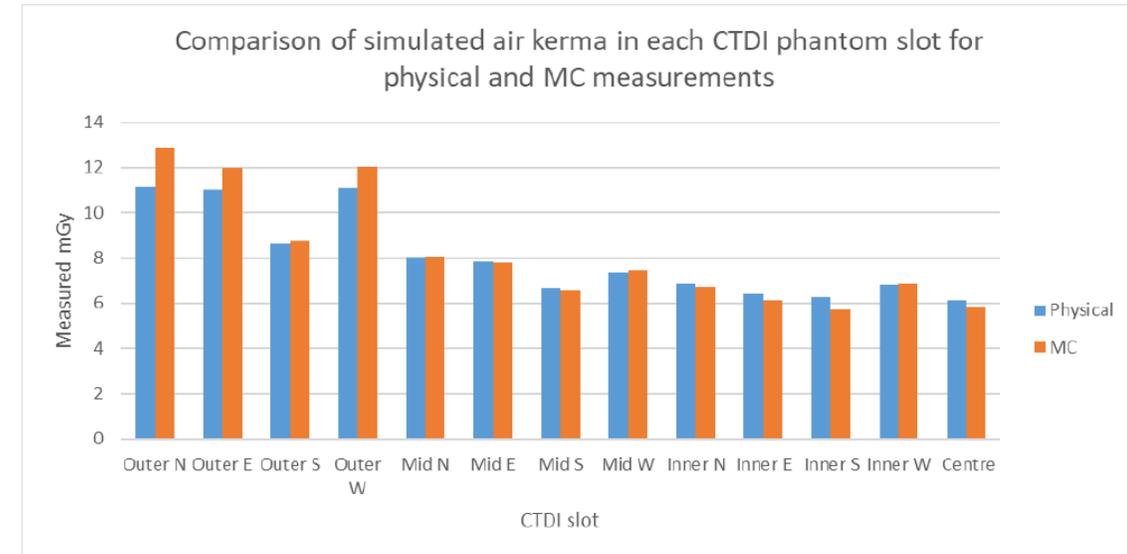
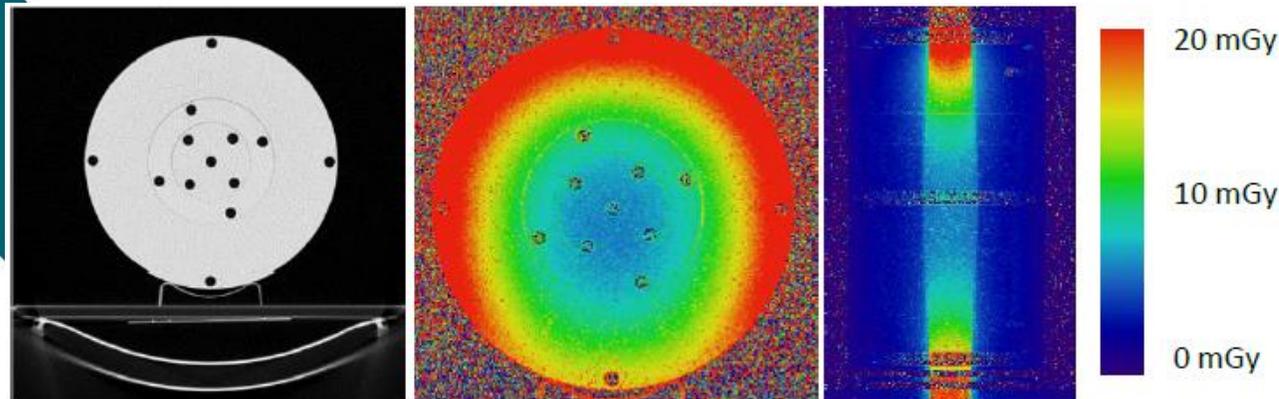
# Results: CT Model Generation

- X-axis profile measurements
- Reasonable agreement in the central 20 degrees (~43 cm FoV)



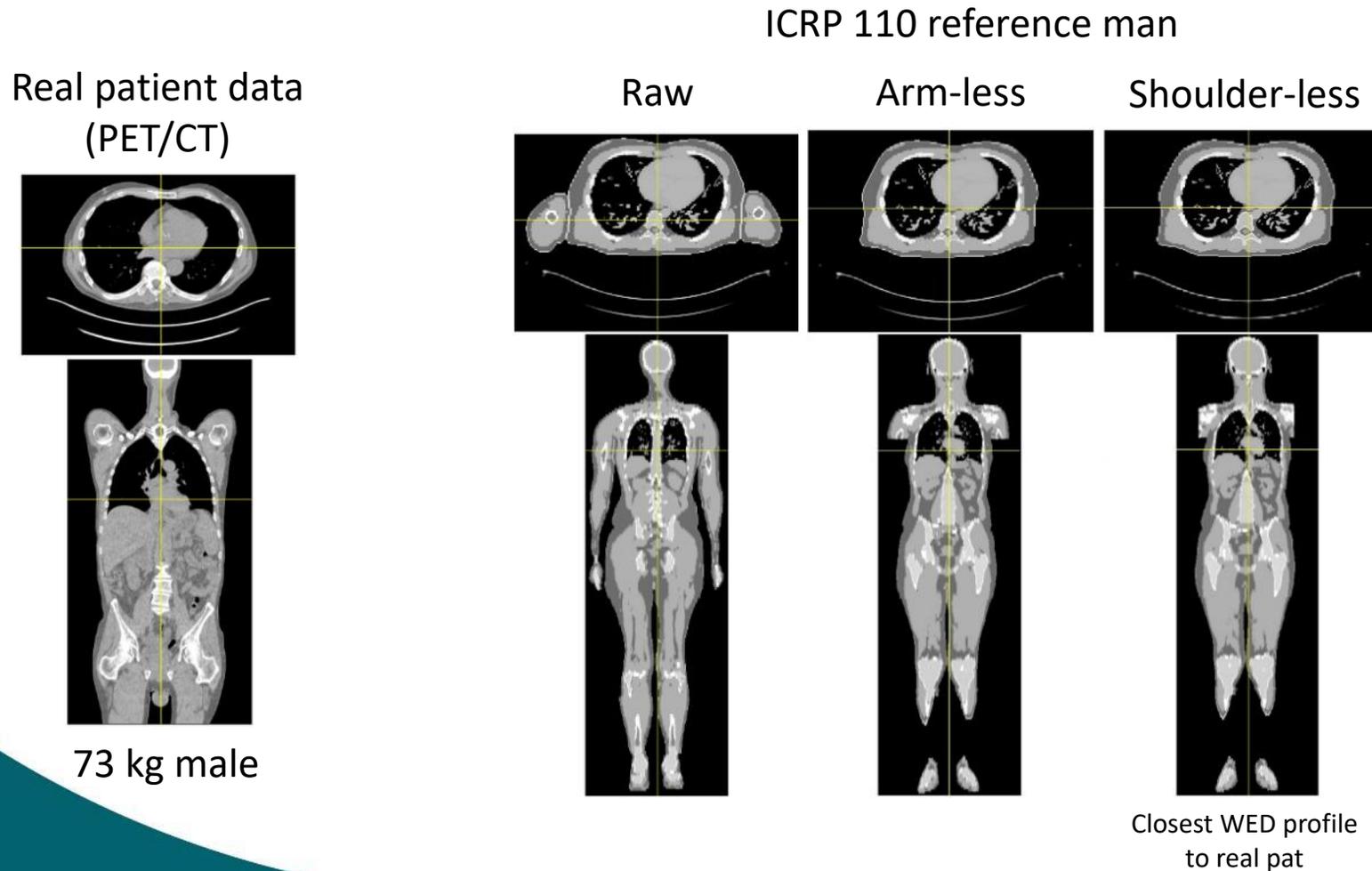
# Results: CT Model Generation

- CTDI chamber measurements in each slot
- Used to derive MC calibration factor
- Generally better than 10% difference
  - Performs best for all slots at depth
- $CTDI_w$
- Phys = 23.54 mGy      Sim = 24.89 mGy
  - 5.7 % diff



# Method: Chest CT Simulation

## Phantom generation 1



I added a couch to these phantoms

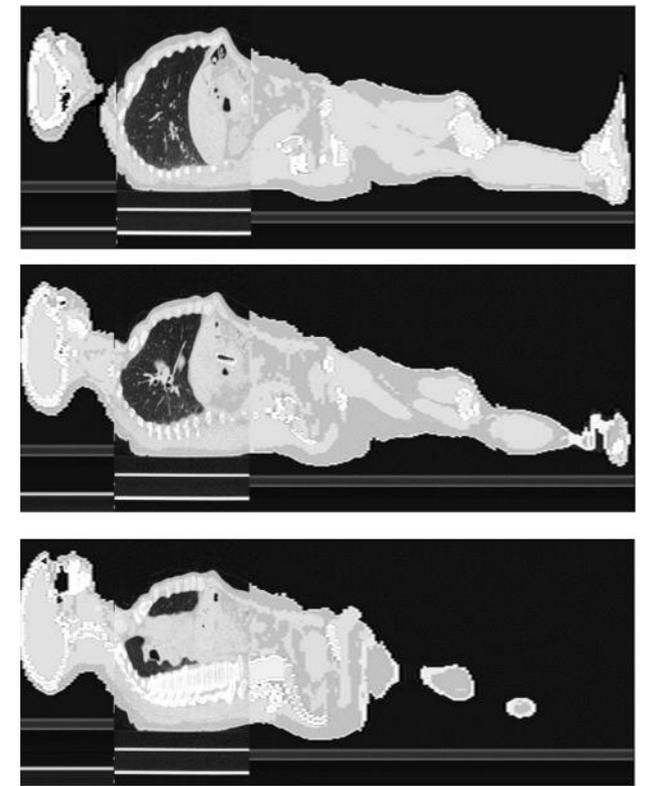
(Also did a sim using the raw phantom w/o a couch)



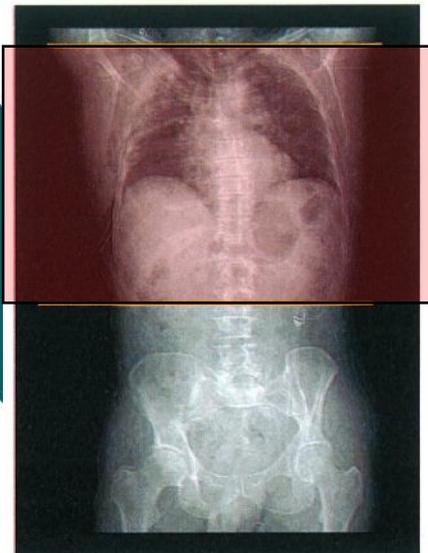
# Method: Chest CT Simulation

## *Phantom generation 2*

- Match scan (and image) range to Shrimpton et al [13, 14]
- Anatomy in image-range from real patient
- Everything else from ICRP 110 phantom



Chest – typical protocol



**Clinical indication:** query lung cancer

**Typical scan justification:** query lung cancer/metastases/malignancy/tumour/neoplasm

Could include: *query cause of shadowing. Query lymphadenopathy. Previous lymph node enlargement. Bulky hilum (that persist on plain film).*

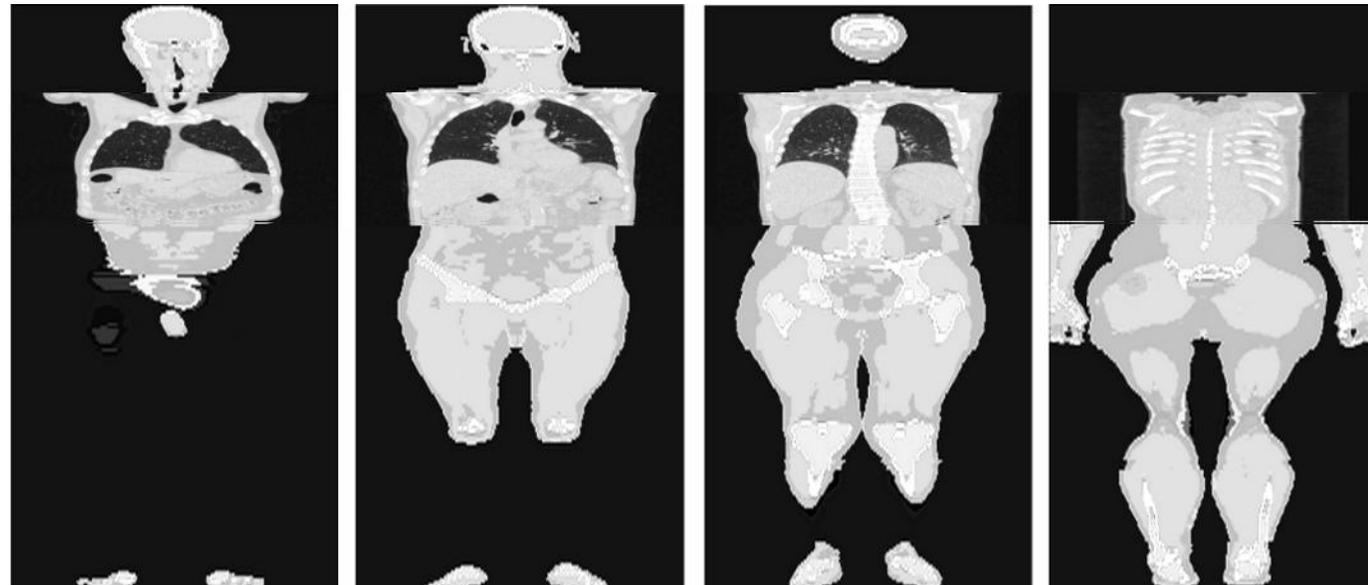
**Scan from:** top of the lungs

**Ending at:** below liver

**Sequences/Phases for examination:** 2

**Contrast used:** Y or N

**Breath held:** Y or N



# Method: Chest CT Simulation

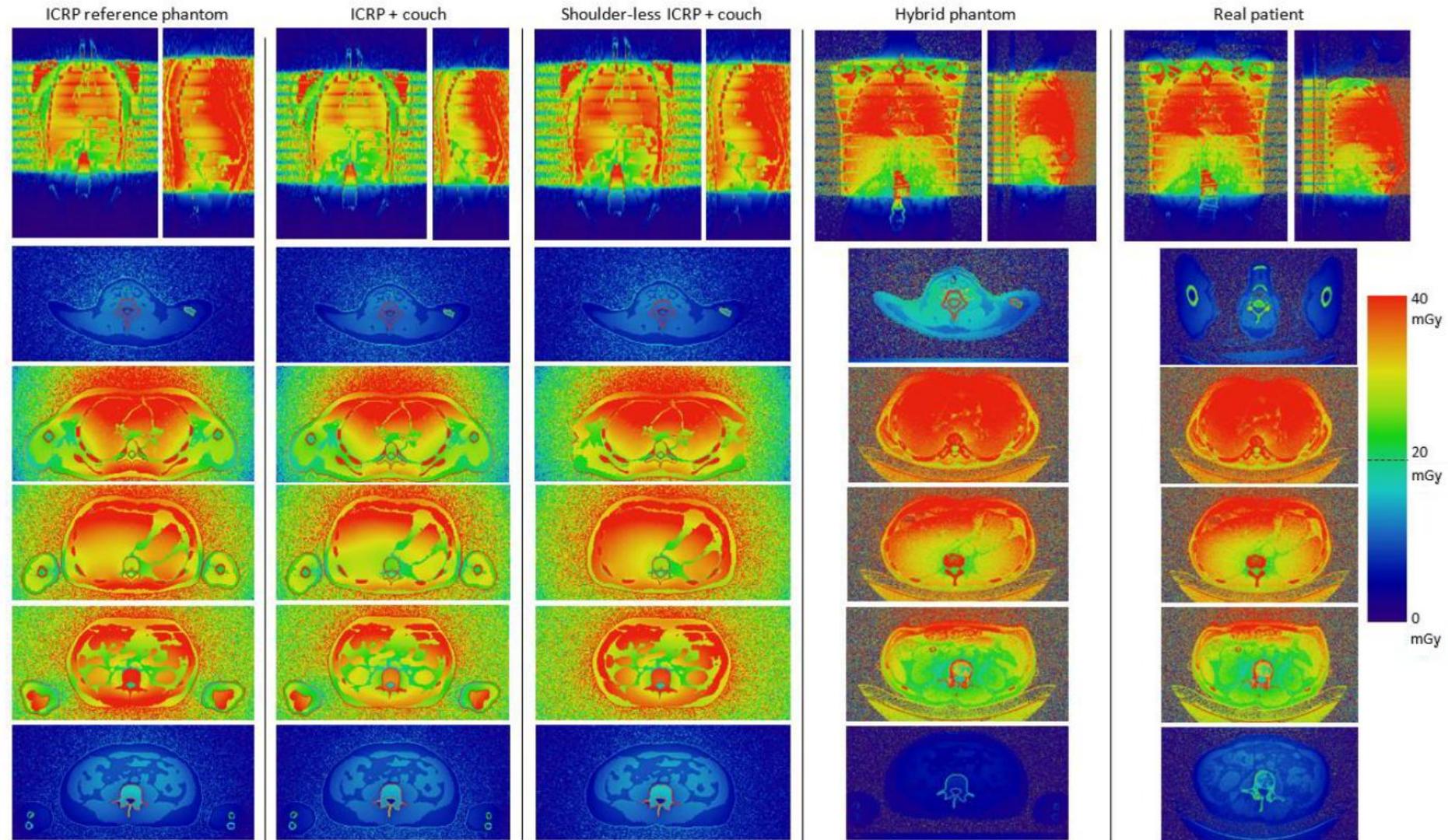
- Used my phase space source to simulate 120kVp, 400 mAs / rotation
- Apices of lungs to inferior liver
- 20 million primaries per projection
- 120 projections per rotation
- Simulations managed via bash script
- Extant organ outlines for real patient
  - .rtstruct already generated for another project<sup>[14]</sup>
  - Limbus RT AI outlining software
  - Used Python for .rtstruct processing and dosimetry

Simulation	Duration (days)
Raw ICRP110 phantom	3
ICRP110 + couch	3
Shoulder-less ICRP110 + couch	3
Real patient	13
Hybrid phantom	26

The sim duration varied chiefly due to phantom matrix size.

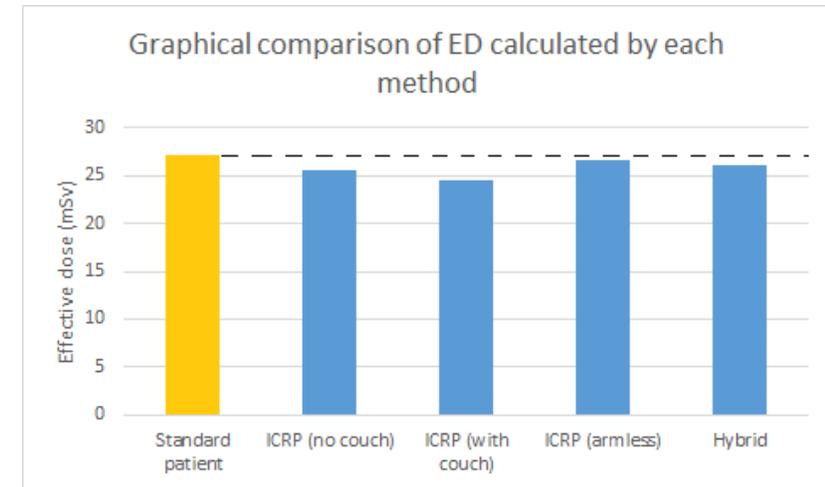


# Results: Chest CT Simulation 1



## Results: Chest CT Simulation 2

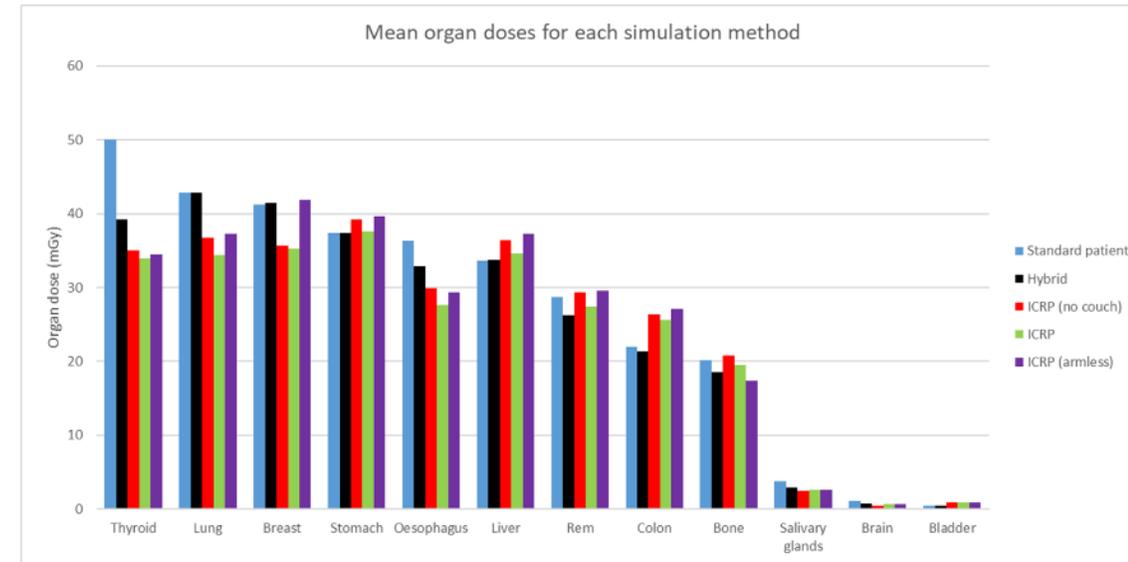
- Shrimpton vs ICRP sim provides more assurance / validation
  - **0.028** here vs 0.027 mSv.[mGy.cm]<sup>-1</sup> in Shrimpton et al<sup>[13]</sup>
- Simulation of the real patient data-set taken as gold-standard
  - Guaranteed anatomical realism



Phantom/patient	Scan-length (cm)	CTDI <sub>w</sub> (mGy)	DLP (mGy.cm)	E <sub>D</sub> (mSv)	E compared to standard patient	E/DLP (mSv.[mGy.cm] <sup>-1</sup> )
Standard patient	40.2	23.5	994	27.1	-	0.027
Hybrid phantom				26.0	-4.0%	0.025
ICRP (no couch)	38.4		904	25.7	-5.4%	<b>0.028</b>
ICRP (couch)				24.6	-9.2%	0.027
ICRP (couch, arm-less)				26.6	-1.9%	0.029

# Results Chest CT Simulation 3

- Mean absorbed doses to radio-biologically relevant organs



Organ	Real patient		ICRP (no couch)		ICRP (with couch)		ICRP (with couch, no arms)		Hybrid phantom	
	mGy	Diff to real	mGy	Diff to real	mGy	Diff to real	mGy	Diff to real	mGy	Diff to real
Thyroid	50.0	-	35.0	-30.0%	34.0	-32.0%	34.5	-31.1%	39.2	-21.6%
Lung	42.9	-	36.7	-14.4%	34.4	-19.7%	37.3	-13.1%	42.9	-0.1%
Breast	41.3	-	35.7	-13.6%	35.3	-14.6%	41.9	1.5%	41.4	0.3%
Stomach	37.4	-	39.2	4.8%	37.6	0.6%	39.7	6.1%	37.4	0.1%
Oesophagus	36.3	-	29.9	-17.8%	27.7	-23.9%	29.3	-19.3%	32.9	-9.5%
Liver	33.6	-	36.4	8.4%	34.6	3.0%	37.2	10.8%	33.8	0.5%
Rem	28.8	-	29.4	2.2%	27.5	-4.5%	29.6	2.8%	26.3	-8.5%
Colon	22.0	-	26.4	19.9%	25.6	16.5%	27.1	23.1%	21.3	-3.2%
Bone	20.2	-	20.8	3.2%	19.5	-3.6%	17.4	-13.8%	18.6	-7.9%
Salivary glands	3.8	-	2.4	-35.2%	2.6	-31.4%	2.6	-31.2%	2.8	-24.4%
Brain	1.1	-	0.5	-58.0%	0.6	-43.8%	0.6	-45.2%	0.7	-34.7%
Bladder	0.4	-	0.8	110.6%	0.9	133.4%	0.9	135.7%	0.4	10.5%

Hybrid phantom closest to real pat in all but 2 organs

# Conclusions

- The Monte Carlo CT model was validated
- The hybrid phantom was a viable method for accurate organ dosimetry
  - However labour-intensive and time-consuming
  - Still exhibited limitations – boundary organs, outline accuracy, RBM, skin etc.
- Simple modifications to the ICRP phantom also increased patient-realism and accuracy
  - Added couch reduced  $E_D$  by 4 %
  - Arms-up 8 % higher  $E_D$ /DLP (note no AEC modelled)
- All tested methods achieved consistency/reasonable accuracy for current uses of  $E_D$



# Further work, limitations, and comments

- This work only used a 'standard-sized' male
  - Did not directly model RBM, skin
    - More a limitation of the outlines than the phantom
- Repeat with a population of varying habitus and gender
  - Would require non-standard sized ref phantoms<sup>[15]</sup>
  - Consider other kVp and CarekV
- Improve CT model
  - Helical scanning
  - 3D AEC
  - Other novel features?
- Analogous, and more sophisticated, project completed by Fu et al<sup>[17]</sup>
  - Used AI to generate the hybrid phantom
  - Is this the way forward?





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**Thank you for listening**

*Any questions?*

# References

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