GATE-RTION
for independent dose calculation: Implementation at the Christie

GATE workshop - PTCOG58

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The Christie NHS Foundation Trust

Conflicts of interest

- None

Overview

1. Monte-Carlo implementation at the Christie
2. Beam-modelling
3. Treatment plan re-calculation
4. Comparison against physical measurements
5. Other issues:
    - Simulation time
    - LET

1. Proton Therapy at the Christie

- Delivery system: Varian ProBeam
  - 3 matched pencil-beam-scanning treatment rooms
    - Gantry: 360°
    - Couch: 6 degrees-of-freedom (Only x,y,z,Θ used in practice)
    - Energy range: 70 – 245 MeV
    - Pre-absorber: 0, 2, 3, 5 cm Lexan (physical thickness)
  - 1 research room
    - Fixed beamline
    - Due to open: Second half of 2019
- Treatment Planning System: Varian Eclipse
  - Version 13.7
  - Proton Convolution Superposition (PCS) algorithm used for dose calculation.
- Clinical delivery:
  - First patient: December 2018
  - Patients started to date: 46

1. Proton Therapy at the Christie: Monte Carlo

- 2 identical Linux clusters:
  - Clinical cluster: For routine plan verifications
  - Development cluster: For research work / Backup for clinical cluster

- Hardware (each cluster):
  - 8× Intel Xeon E3-1240 @ 3.7 GHz
  - → Total of 40 cores

- Software:
  - Geant4 v. 10.3.3
  - GATE v. 8.1 (GATE RTion)
  - Octave v. 4.2.2
  - AutoMC v. 0.7.4 (In-house Octave code)

1. AutoMC: In-house Monte-Carlo using GATE RTion

- AutoMC main features:
  - Automated beam-model tuning
  - Automated calculation of treatment plans using GATE RTion
  - Automated evaluation of MC vs. TPS dose grid
  - Modular beam-models and CT calibrations
  - Visualisation tools

- What has been commissioned:
  - Beam-model:
    - Varian ProBeam beam-model, generated from Christie commissioning data.
  - CT calibrations:
    - Generated using the stoichiometric calibration process, using the same data as used for the clinical CT calibrations configured in our TPS (Varian Eclipse).

1. AutoMC: Process flow

1. **Dicom export to cluster:**
   - CT, RTSTRUCT, DOSE, RTION
2. **Pre-processing of CT:**
   - CT overrides applied
   - CT image cropped
   - CT calibration applied
3. **Generation of GATE macros:**
   - Dicom RTION file processed to generate the GATE macros to replicate each field
   - Beam-model applied
   - Pre-absorber is configured
4. **GATE RTion simulation:**
   - Each job is split by energy layer and submitted to the cluster
   - AutoMC monitors for completion of the simulation
5. **Post simulation:**
   - The output of each split is combined, and the uncertainty is calculated
   - 3D gamma analysis comparing MC vs. TPS
   - Results written to database

2. Beam-model overview

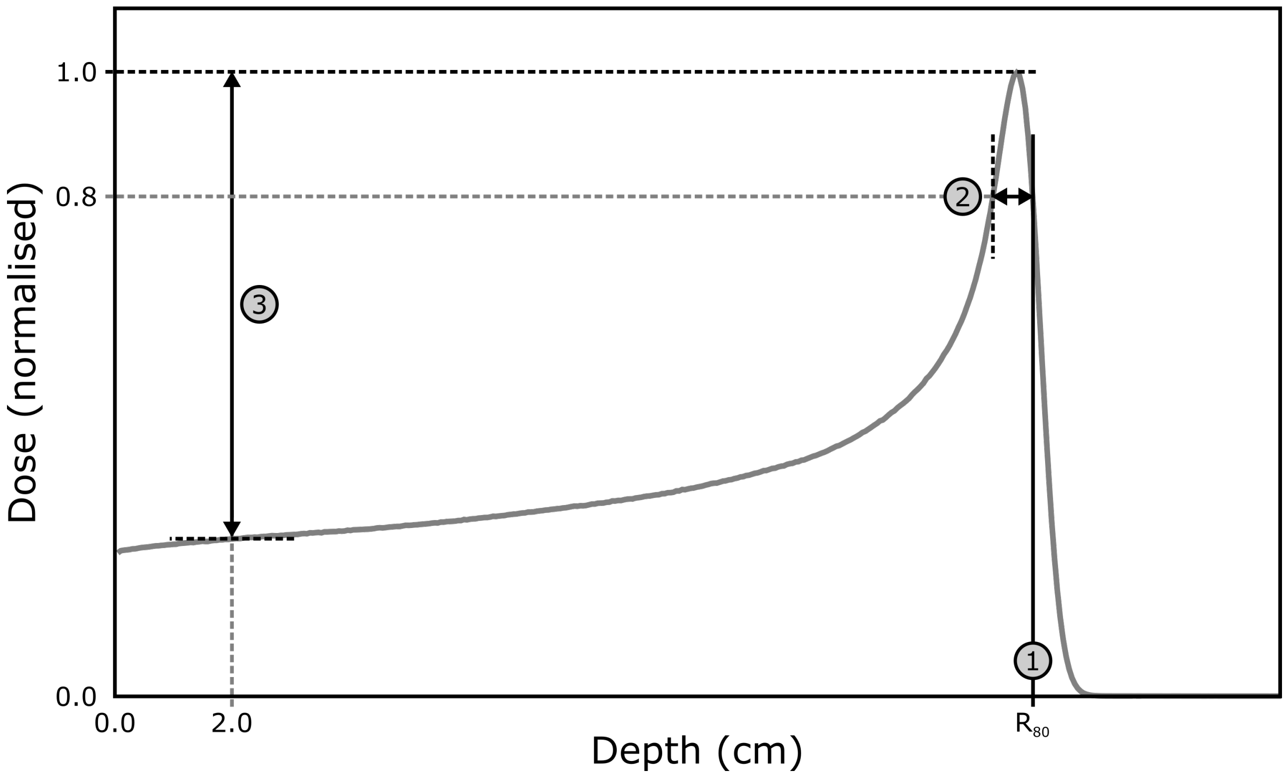
- The Monte-Carlo simulates protons originating from a source plane and travelling into the target (i.e. the CT image).

- The source configuration is tuned to match Christie commissioning data:

1. The source plane is located within the nozzle.
2. Energy (mean and stdev) is tuned to reproduce IDDs in water.
3. The number of protons per MU is tuned to match IDD amplitudes.
4. Source width and optics are defined to match in-air spot profiles.

2. Beam-model overview: Energy tuning

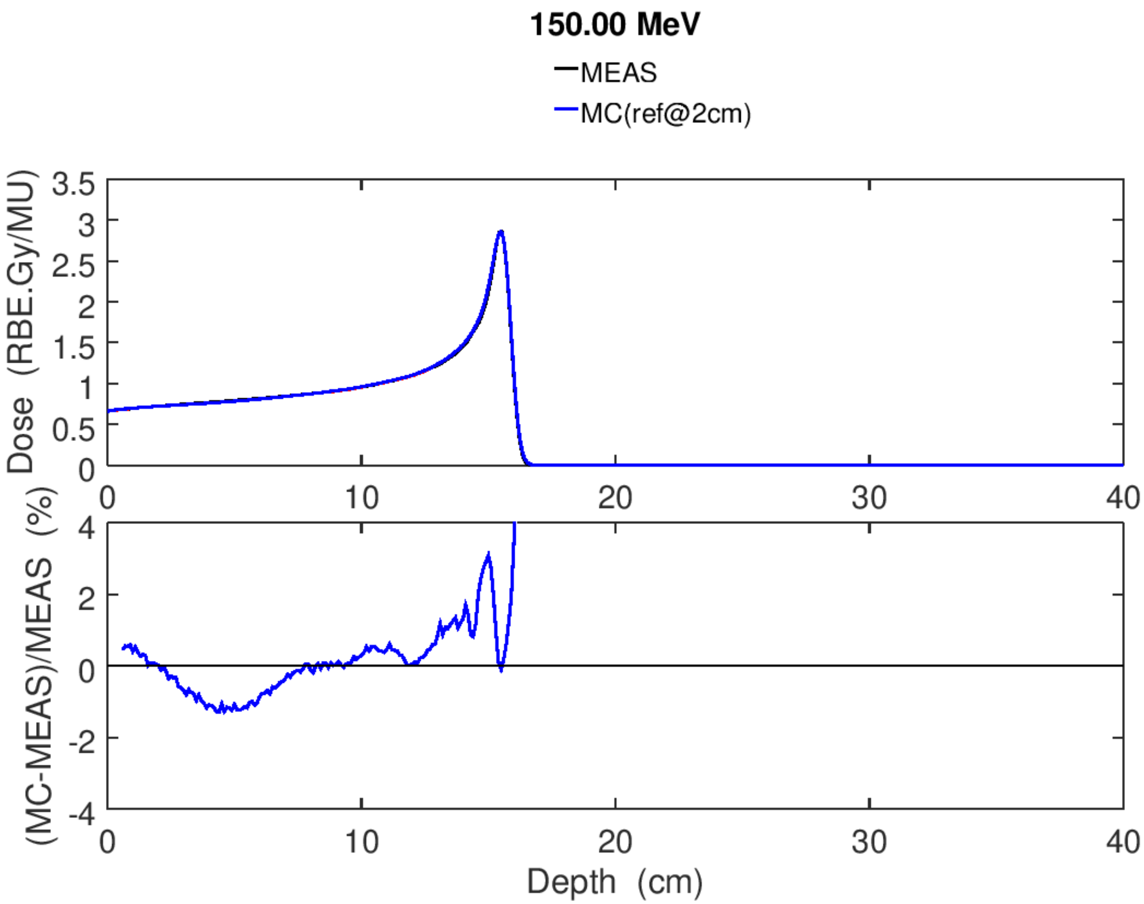
1. Location: $R_{80\%}$
2. Width: $R_{Distal80\%}-R_{Proximal80\%}$
3. Peak-to-entrance ratio: $R_{100\%}/R_{@2cm}$



The Christie

2. Beam-model overview: Energy tuning

- Nominal energy: 150.0 MeV
- Gate energy (mean ± std): 150.3 ± 1.3 MeV



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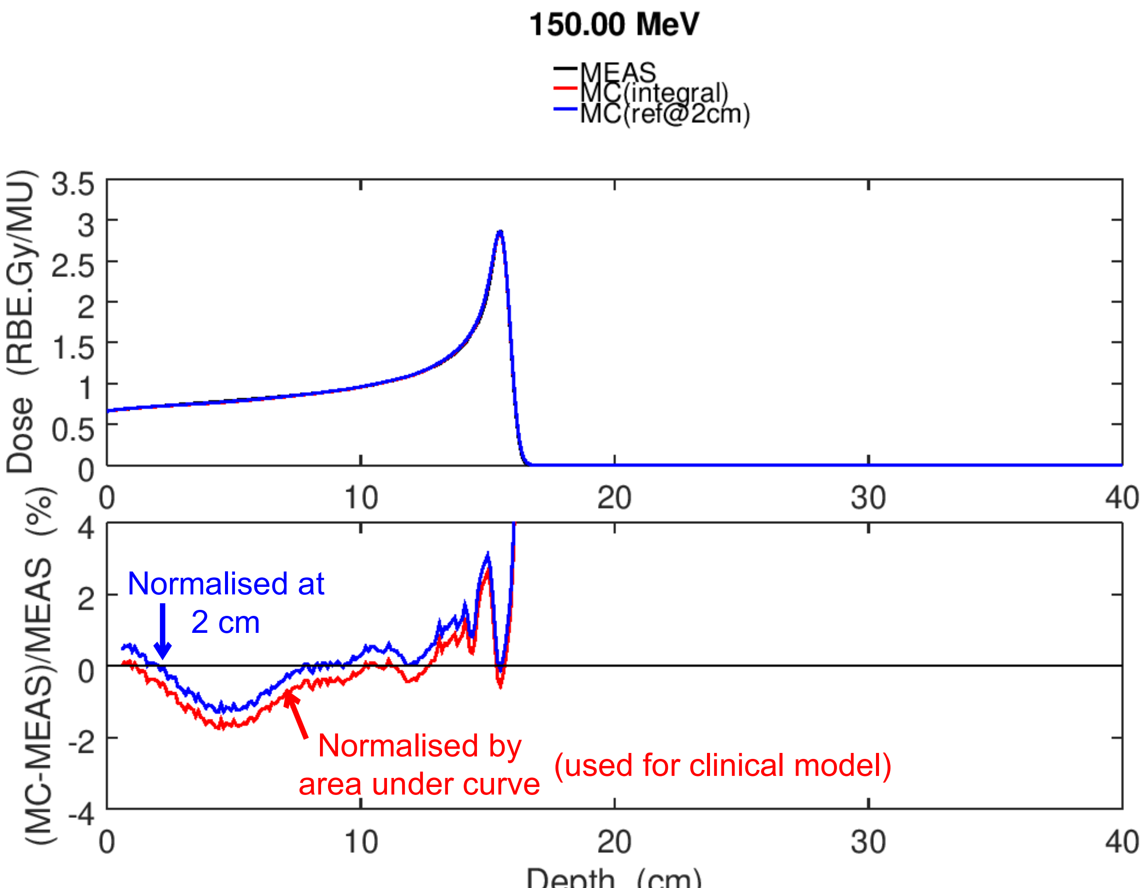
2. Beam-model overview: Protons per MU

- IDD – absolute dose:
  1. Commissioning data: RBE.Gy / MU
  2. Monte-Carlo data: Gy / proton

  → Calculate: RBE * protons / MU



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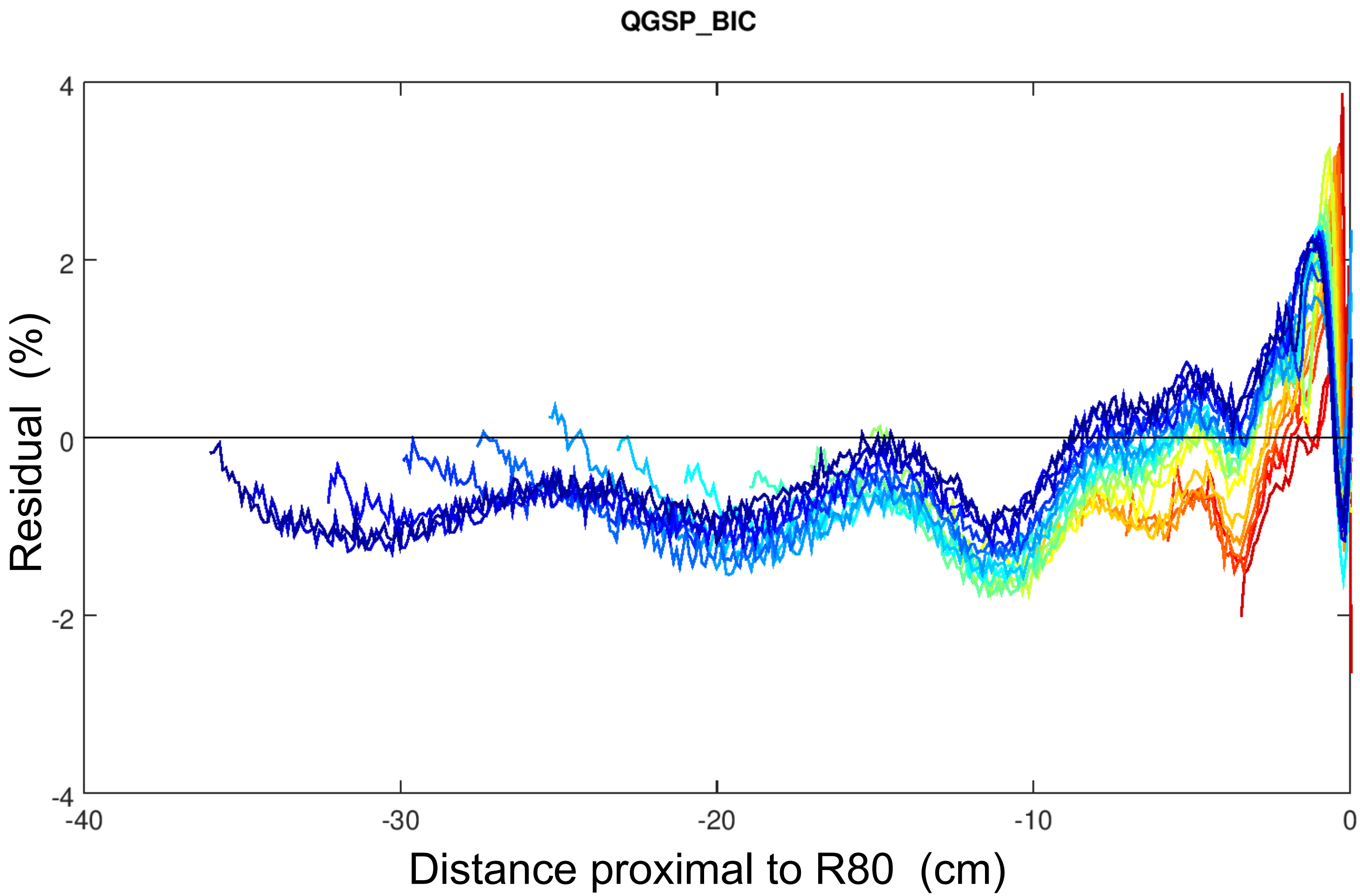
2. Beam-model overview: IDD residuals

- Tuning is repeated for each commissioned energy: 70 - 245 MeV (in 10 MeV steps)

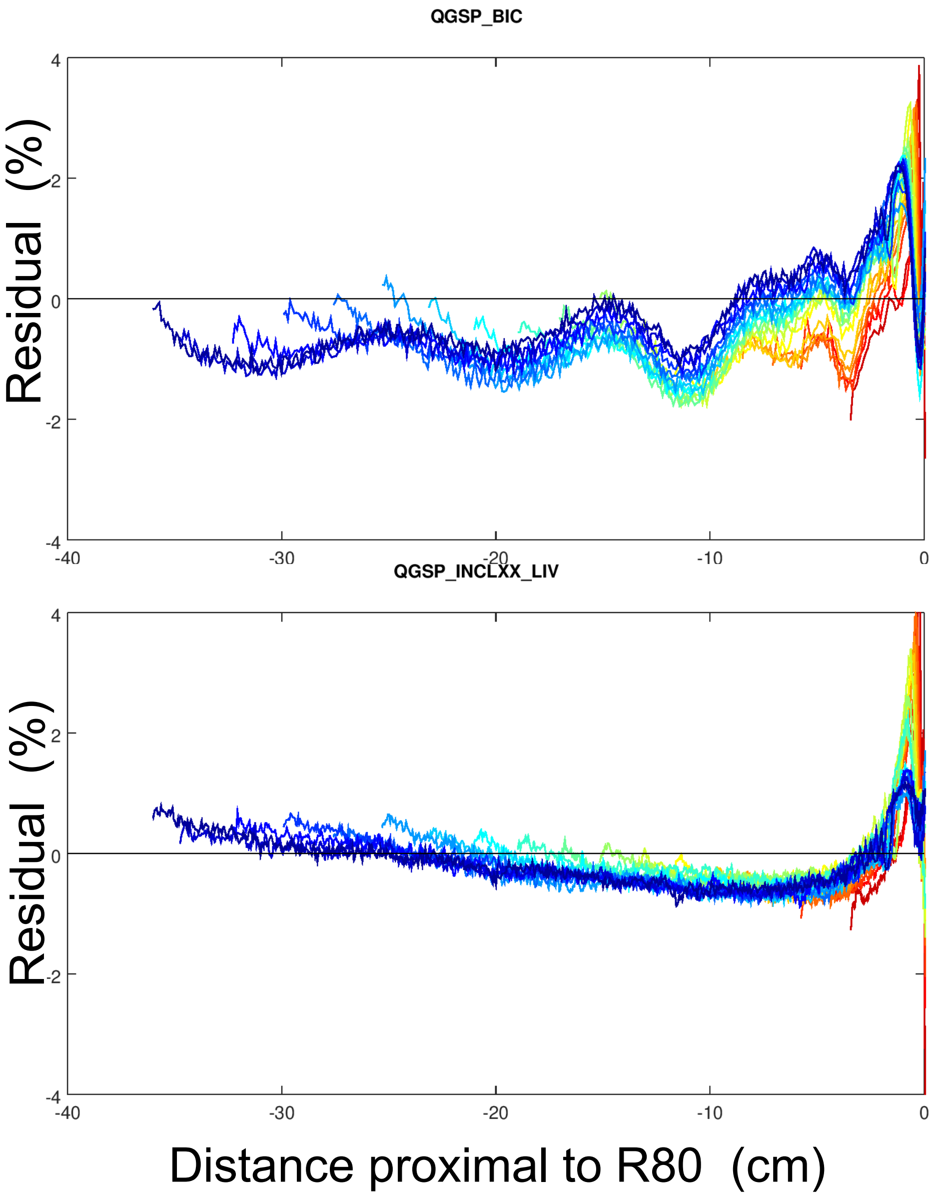


Christie

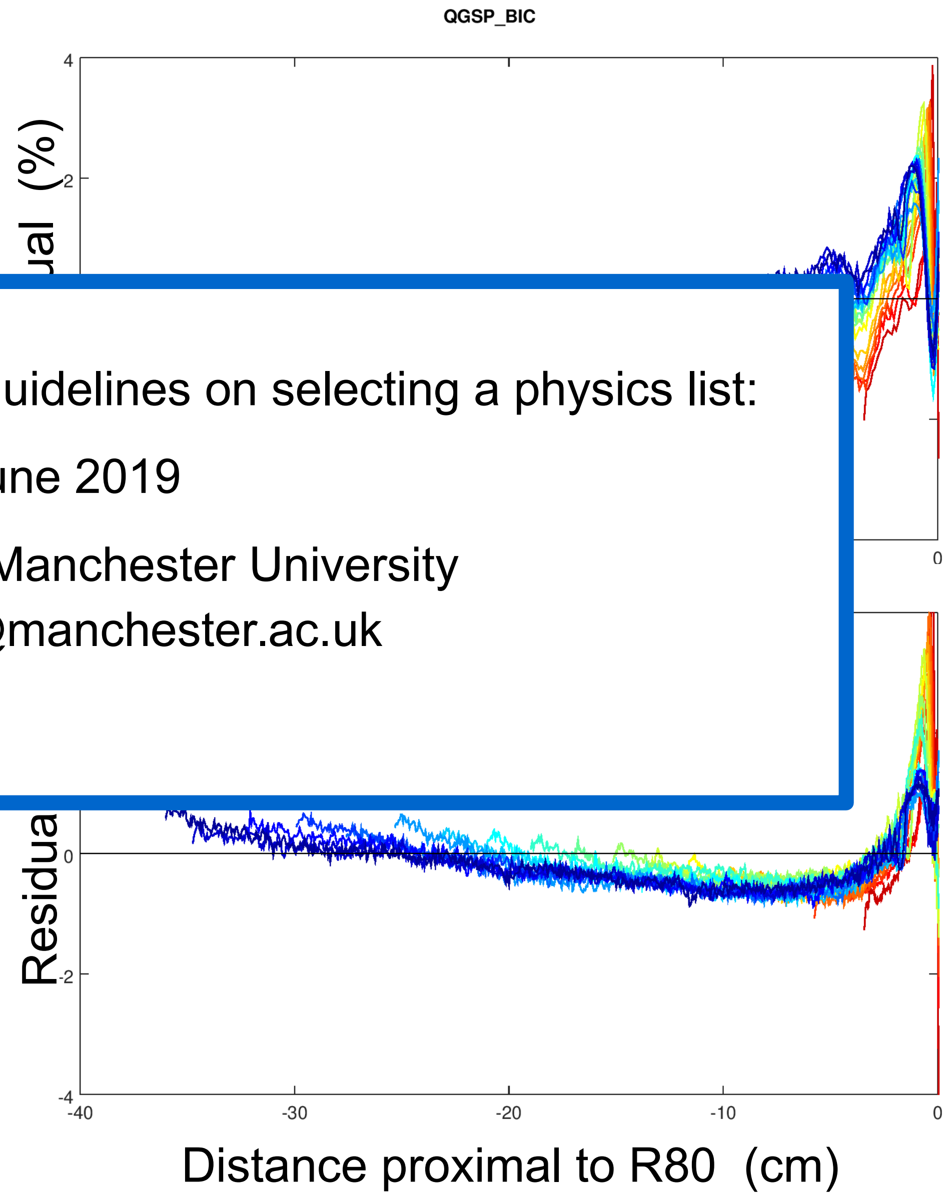
2. Beam-model overview: Physics lists

Current clinical physics list:
QGSP_BIC

Possible alternative physics list?:
QGSP_INCLXX_LIV



2. Beam-model overview: Physics lists



Current clinical physics list:

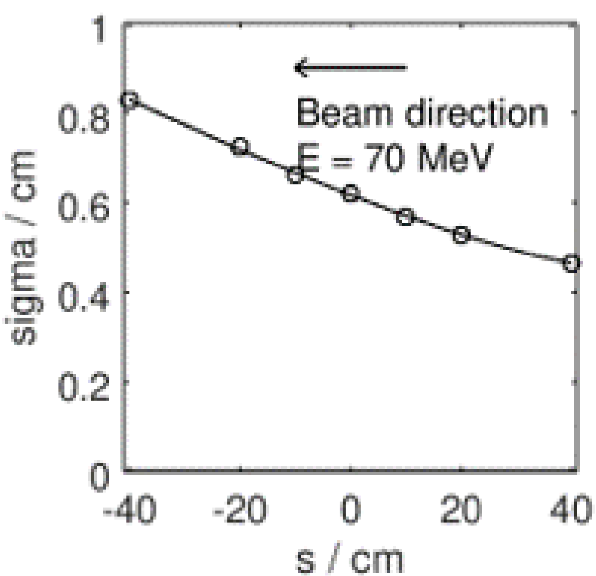
- Collaborative study to establish guidelines on selecting a physics list:
  - STFC funding approved: 7th June 2019
  - Contact: Carla Winterhalter, Manchester University
    Carla.Winterhalter@manchester.ac.uk

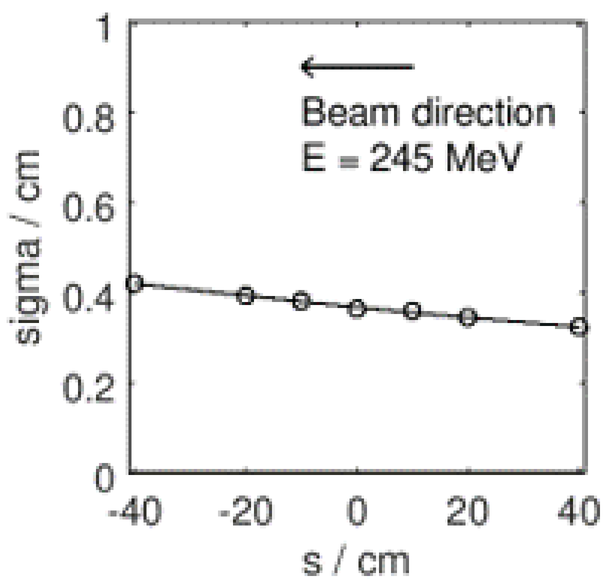
Possible alternative physics list?:
QGSP_INCLXX_LIV

2. Beam-model overview: Optics

- In-air; Without pre-absorber
  - Spot-sizes in-air measured at several positions around isocentre.
  - Repeated across full range of energies.
  - Hyperbolic fits applied.
  - Parameters required by Gate are derived from these fits:

```
– /gate/source/S1/setSigmaX                         3.62
– /gate/source/S1/setEllipseXThetaEmittance         40.67 mm*mrad
– /gate/source/S1/setSigmaTheta                     3.62 mrad
– /gate/source/S1/setEllipseXThetaRotationNorm      positive
```

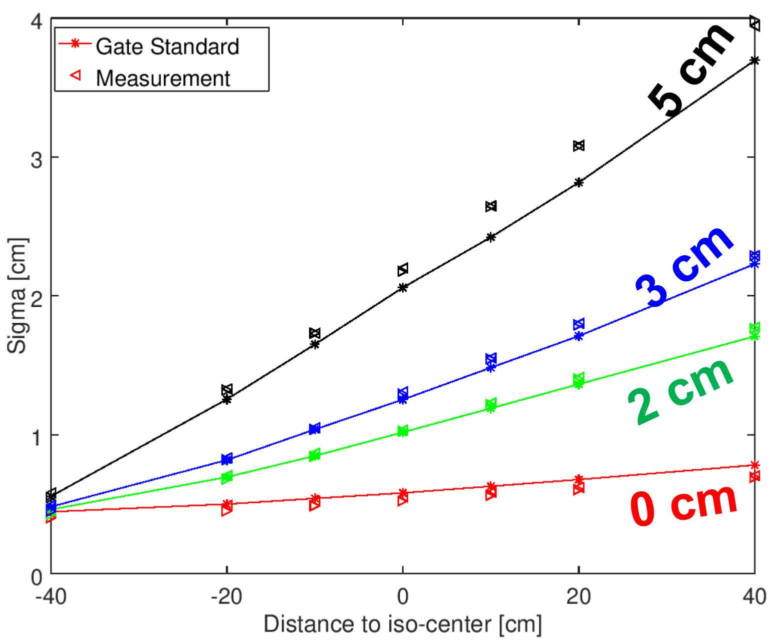




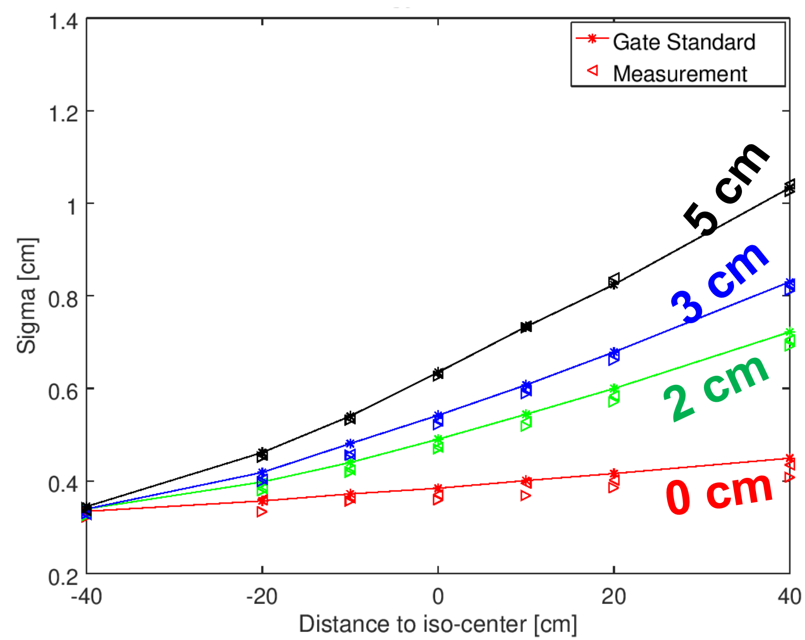
2. Beam-model overview: Optics

- In-air; With pre-absorber
  - Pre-absorber is defined as a physical block in the simulation.
  - Configured to match the material specification provided by the vendor:
    - Composition; Physical density; Location
  - Spot-sizes in-air measured for validation.
    - (Figures courtesy of Carla Winterhalter)

90 MeV



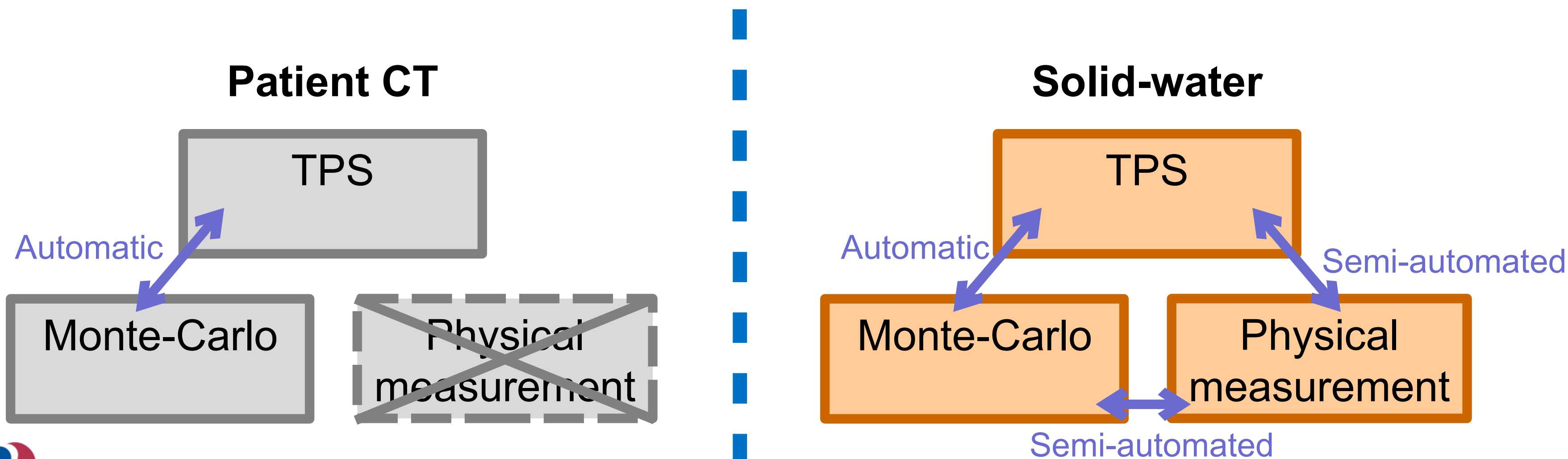
245 MeV



3. Plan re-calculation: Example

- Automated process:
  - No specific Monte-Carlo experience needed for routine use.

- What is simulated:
  - Individual fields in patient CT
  - Individual fields in solid-water



The Christie

3. Plan re-calculation: Example

- Automated process:
  - No specific Monte-Carlo experience needed for routine use.

- What is simulated:
  - Individual fields in patient CT
  - Individual fields in solid-water

- Example case study:
  - 2 phase plan
  - 3-fields per phase
  - 5 cm pre-absorber (physical thickness)

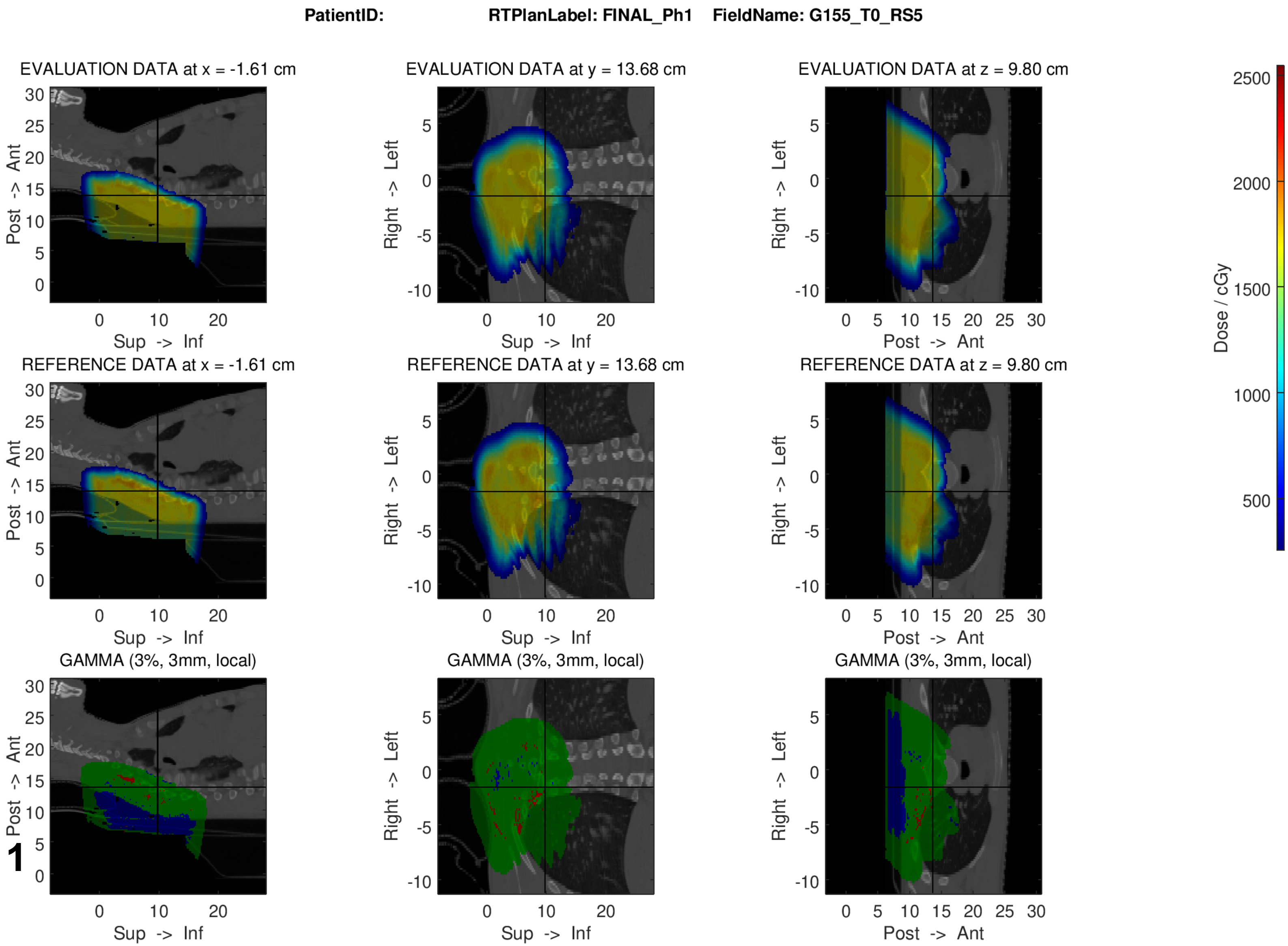
3. Plan re-calculation: Patient CT

TPS

AutoMC

Gamma

95.4% γ ≤ 1



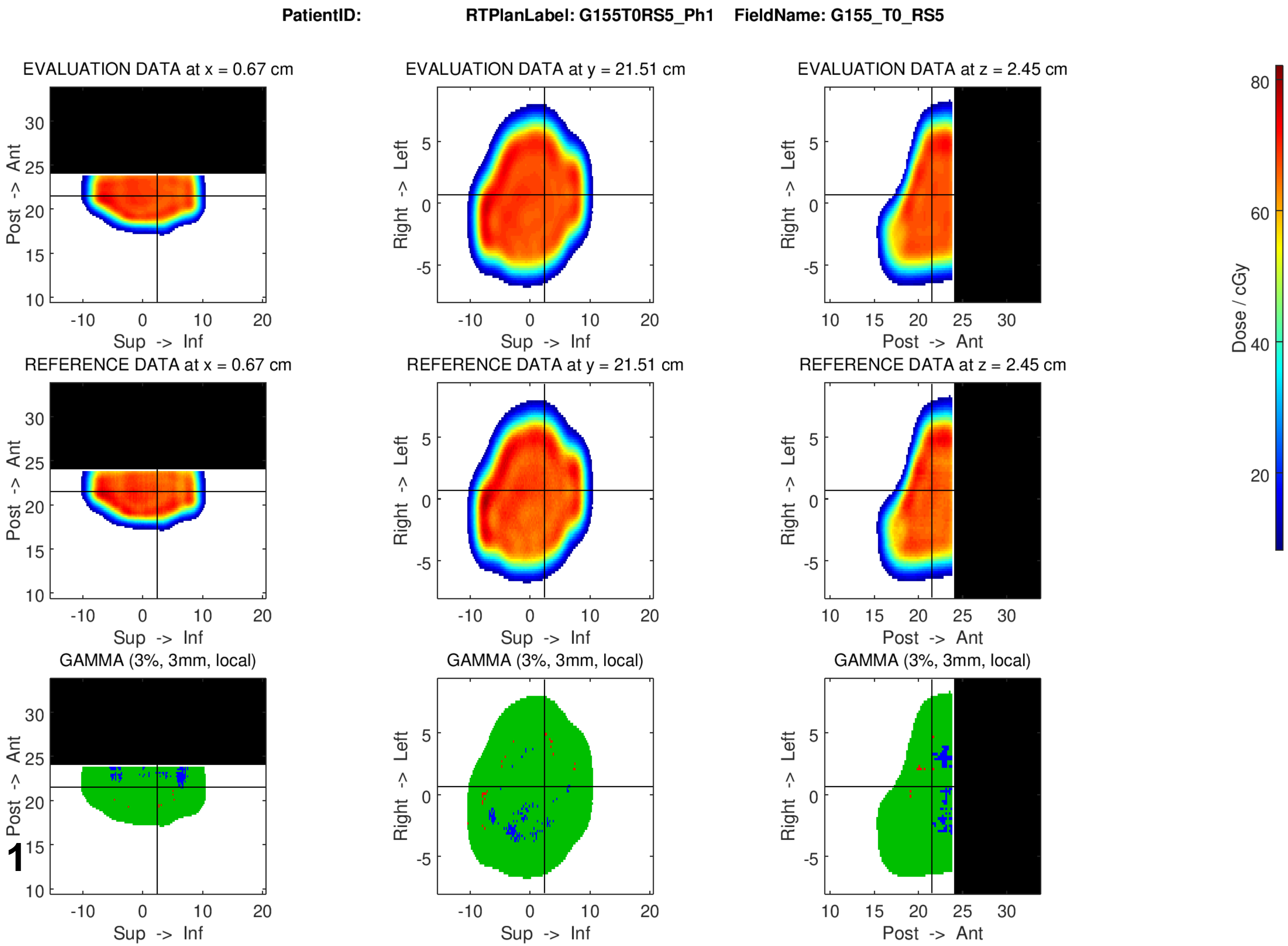
3. Plan re-calculation: Solid-water

TPS

AutoMC

Gamma

96.0% γ ≤ 1



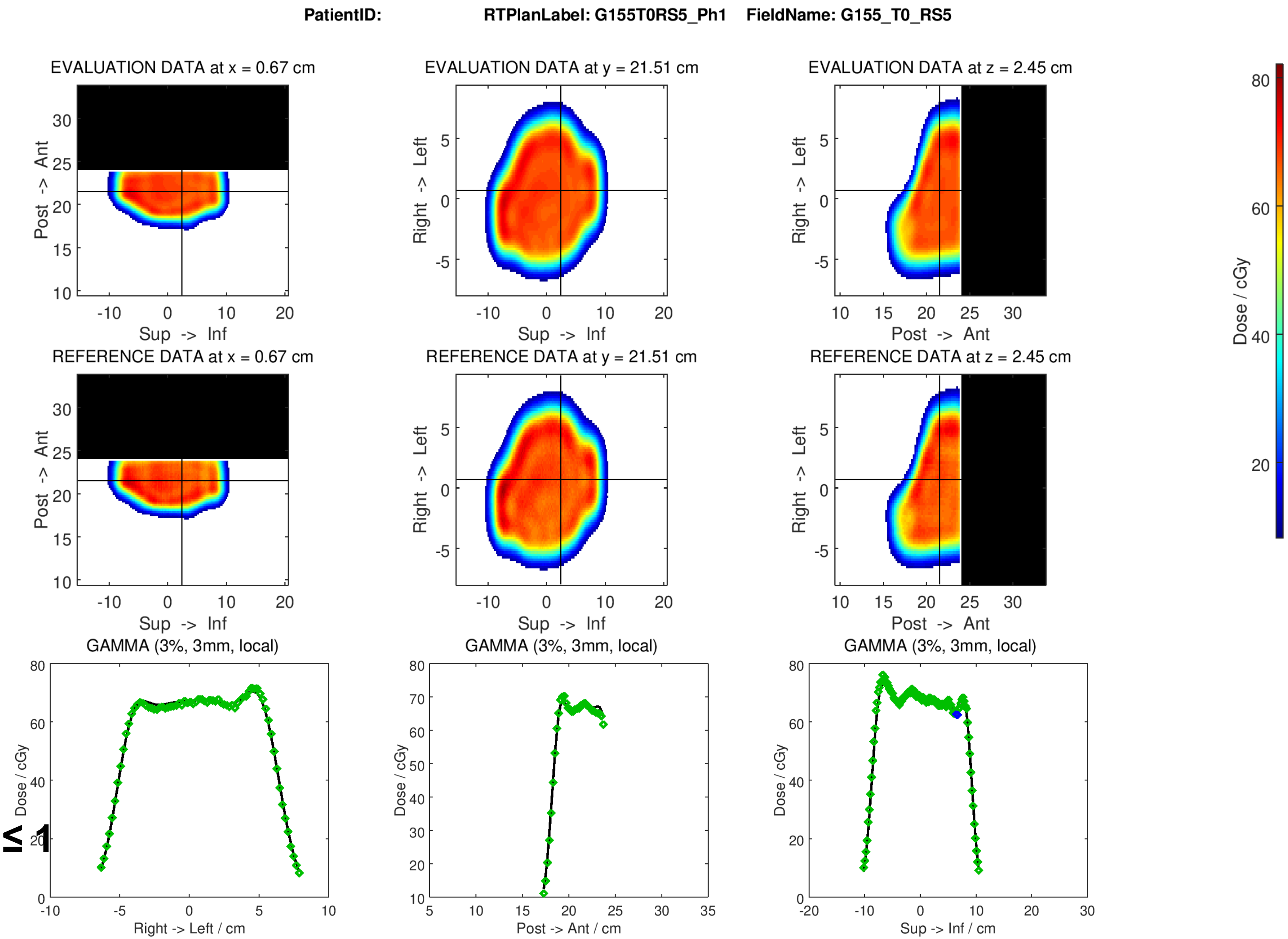
3. Plan re-calculation: Solid-water

TPS

AutoMC

Gamma

96.0% γ ≤ 1



3. Plan re-calculation: Metrics

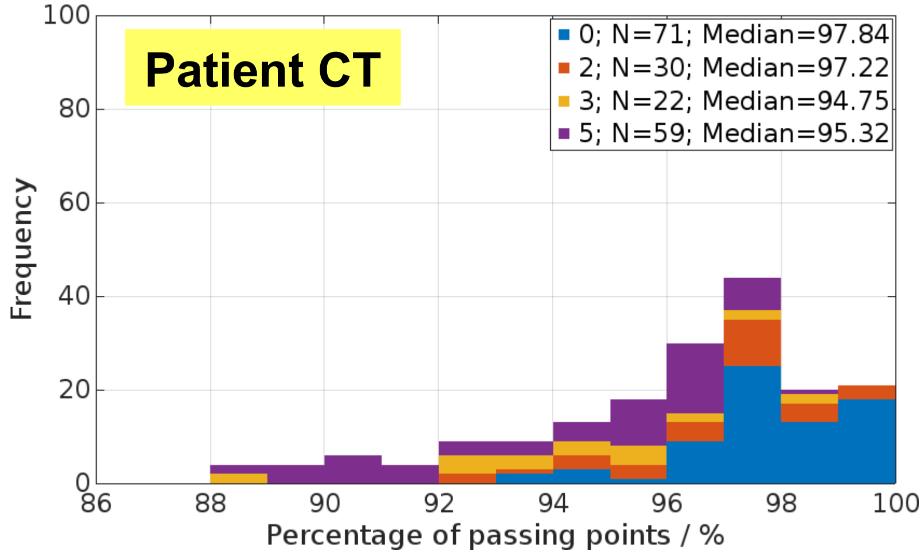
- **MC vs. TPS**
  - 3D gamma
  - Absolute dose difference

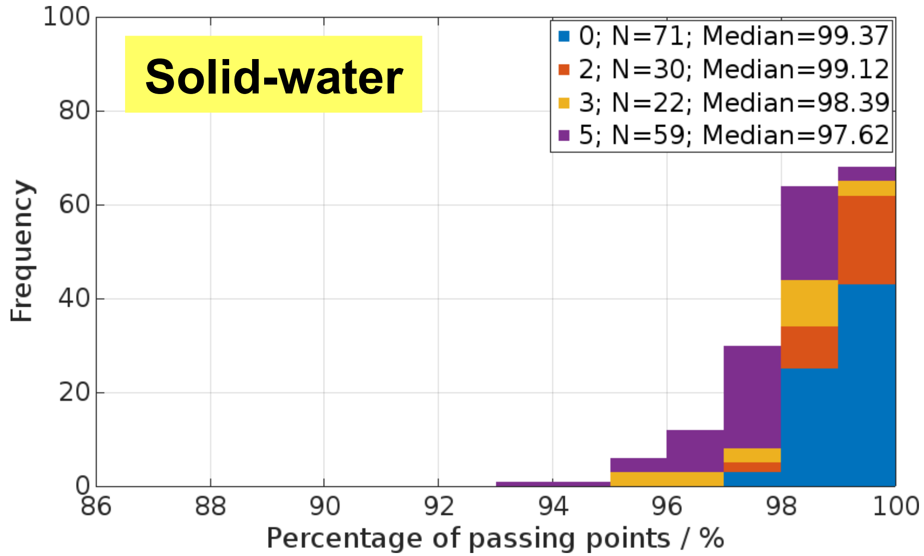
- **TPS vs. Physical measurement**
  - 2D array: 3D gamma
  - Chamber: Absolute dose difference

- **MC vs. Physical measurement**
  - 2D array: 3D gamma
  - Chamber: Absolute dose difference

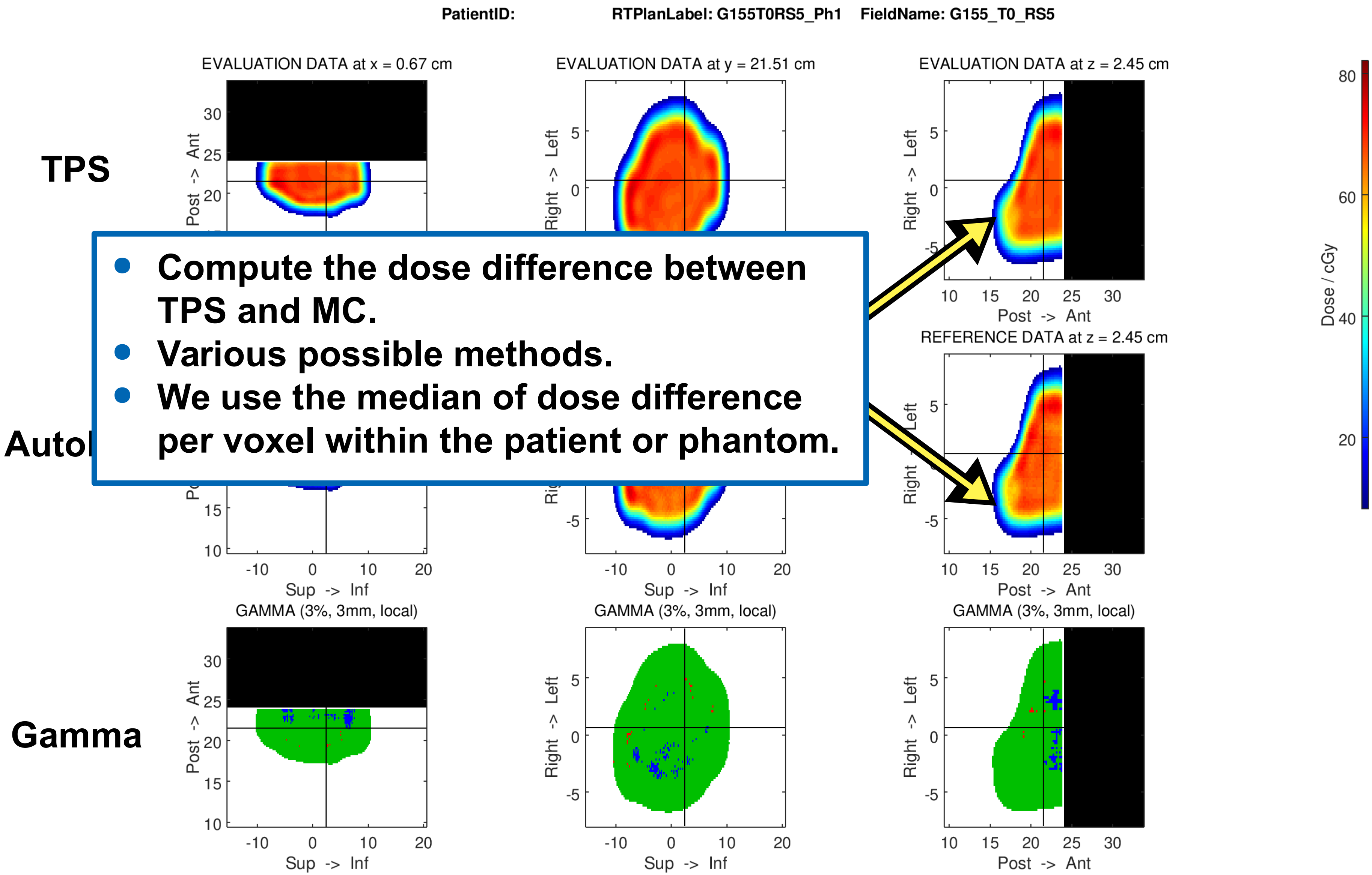
3. MC vs. TPS: 3D gamma analyses

- Gamma settings:
  - 3%, 3 mm
  - Dose distributions are normalised:
    - i.e. Evaluation is of dose distribution shape only.
- Cohort:
  - Patients planned to date: **46**
  - Patients analysed using MC: **46**
  - Fields analysed using MC: **182**
- Results:
  - In solid-water, typically > 95% of voxels have γ ≤ 1.
- Dependence on:
  - CT or solid-water
  - Pre-absorber thickness





3. MC vs. TPS: Absolute dose difference



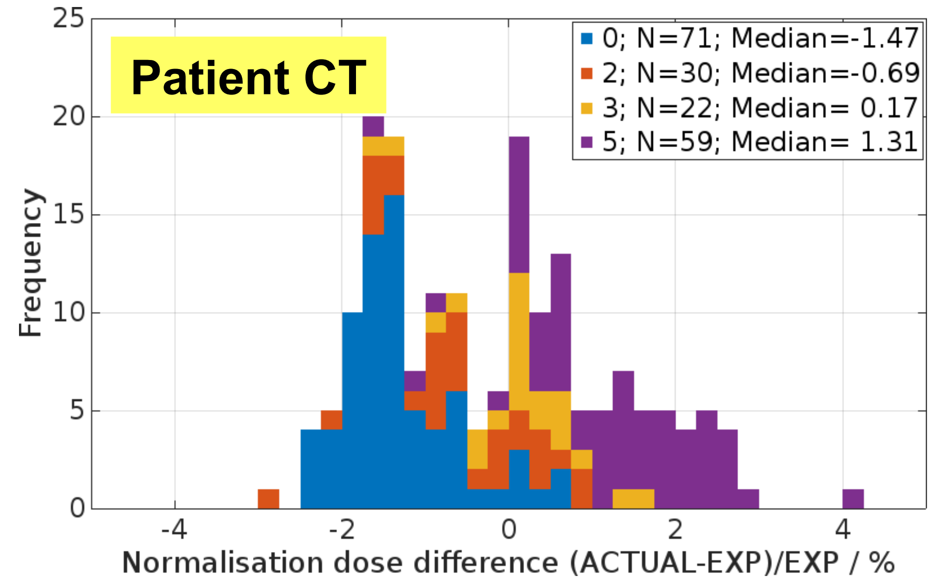
- Compute the dose difference between TPS and MC.
- Various possible methods.
- We use the median of dose difference per voxel within the patient or phantom.

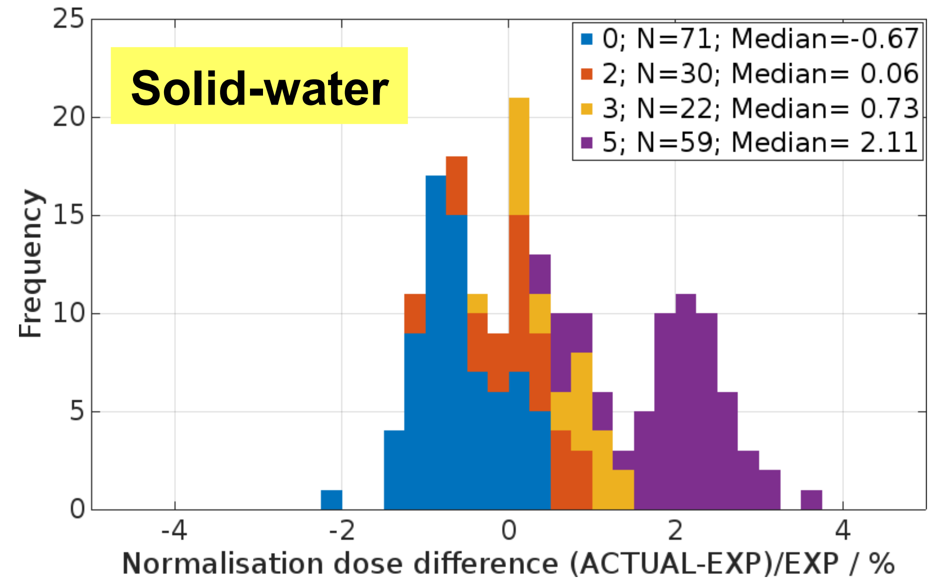
3. MC vs. TPS: Absolute dose difference

- Patients planned to date: **46**
- Patients analysed using MC: **46**
- Fields analysed using MC: **182**

- MC and TPS agree (systematically) within: **+/- 2%**

- Dependence on:
  - Pre-absorber thickness

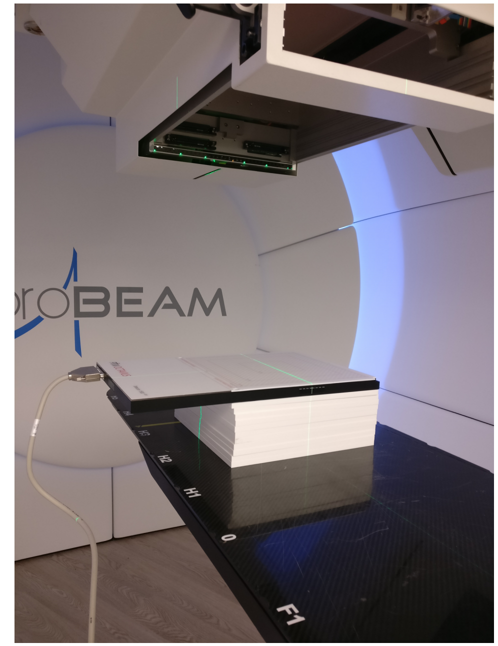




4. Physical Verification

- Physical verification in solidwater using:
  - 2D array: PTW 1500 XDR
  - Chamber: PTW semiflex

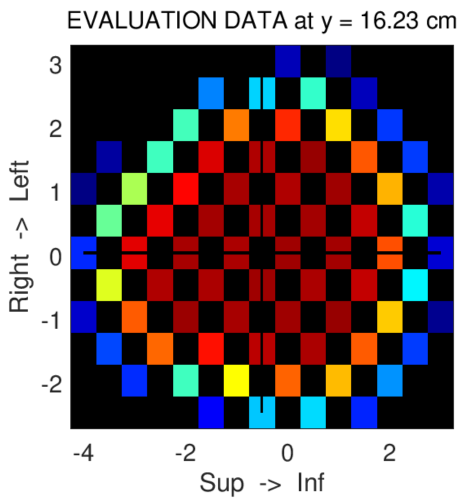
- Measurements typically done at:
  - Gantry angle 0°
  - At least 2 depths



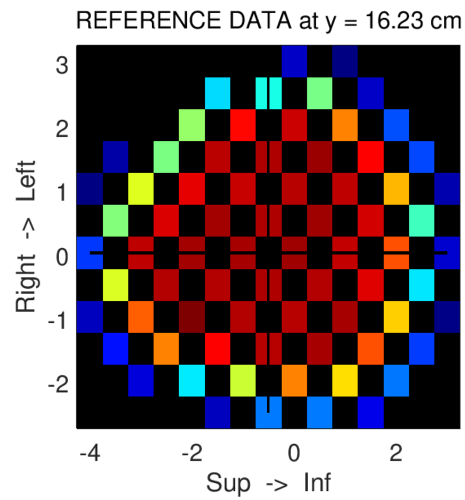
4. Physical Verification: 2D array

- 2D array example measurement.
  - Diameter of each chamber: 0.44 cm
  - Chamber pitch: 1.00 cm

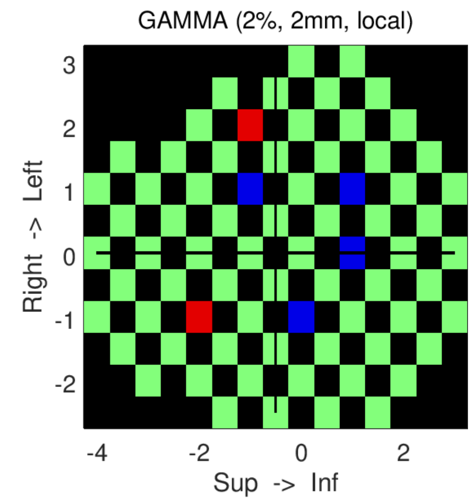
TPS



2D array

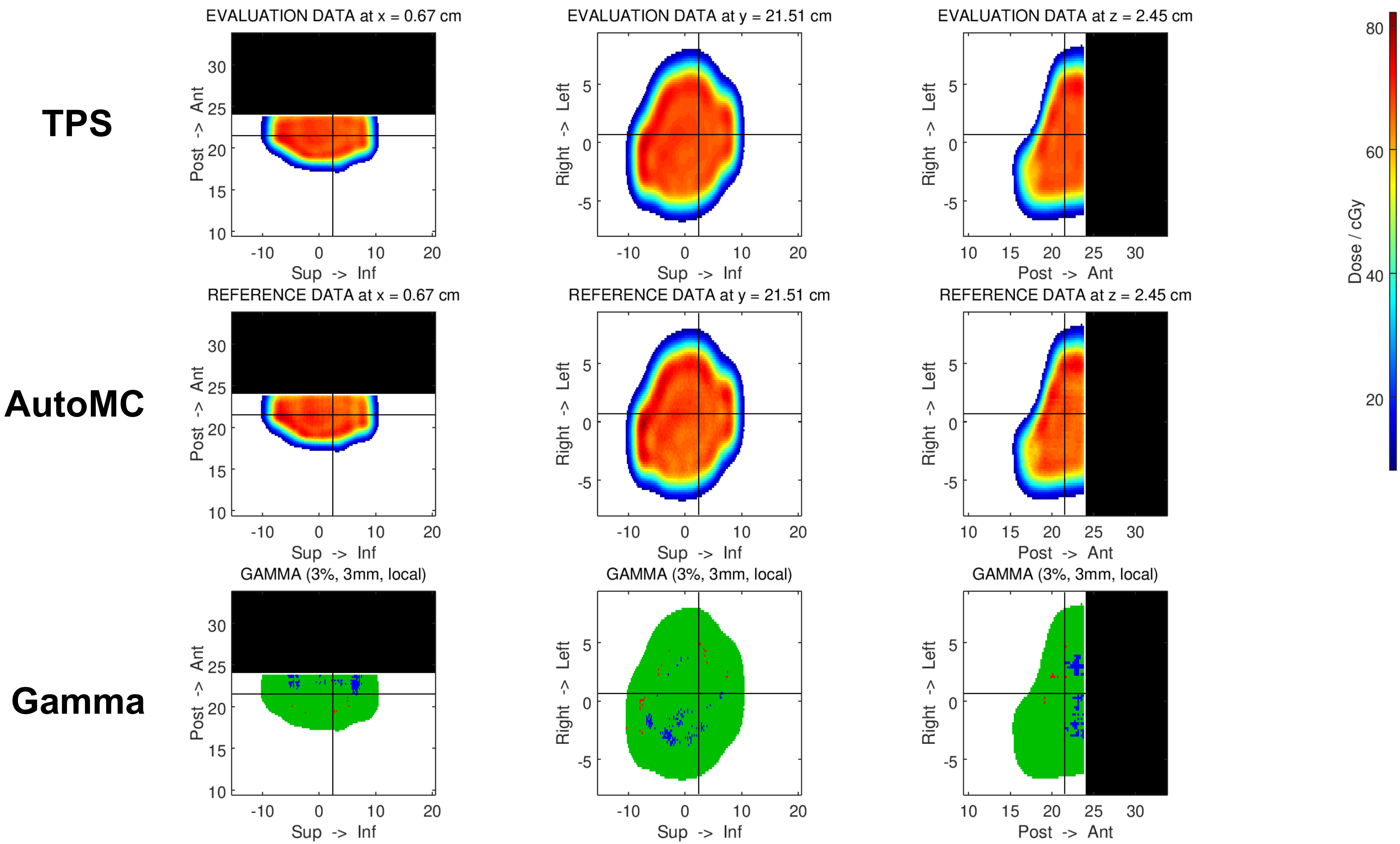


Gamma (2%, 2 mm)

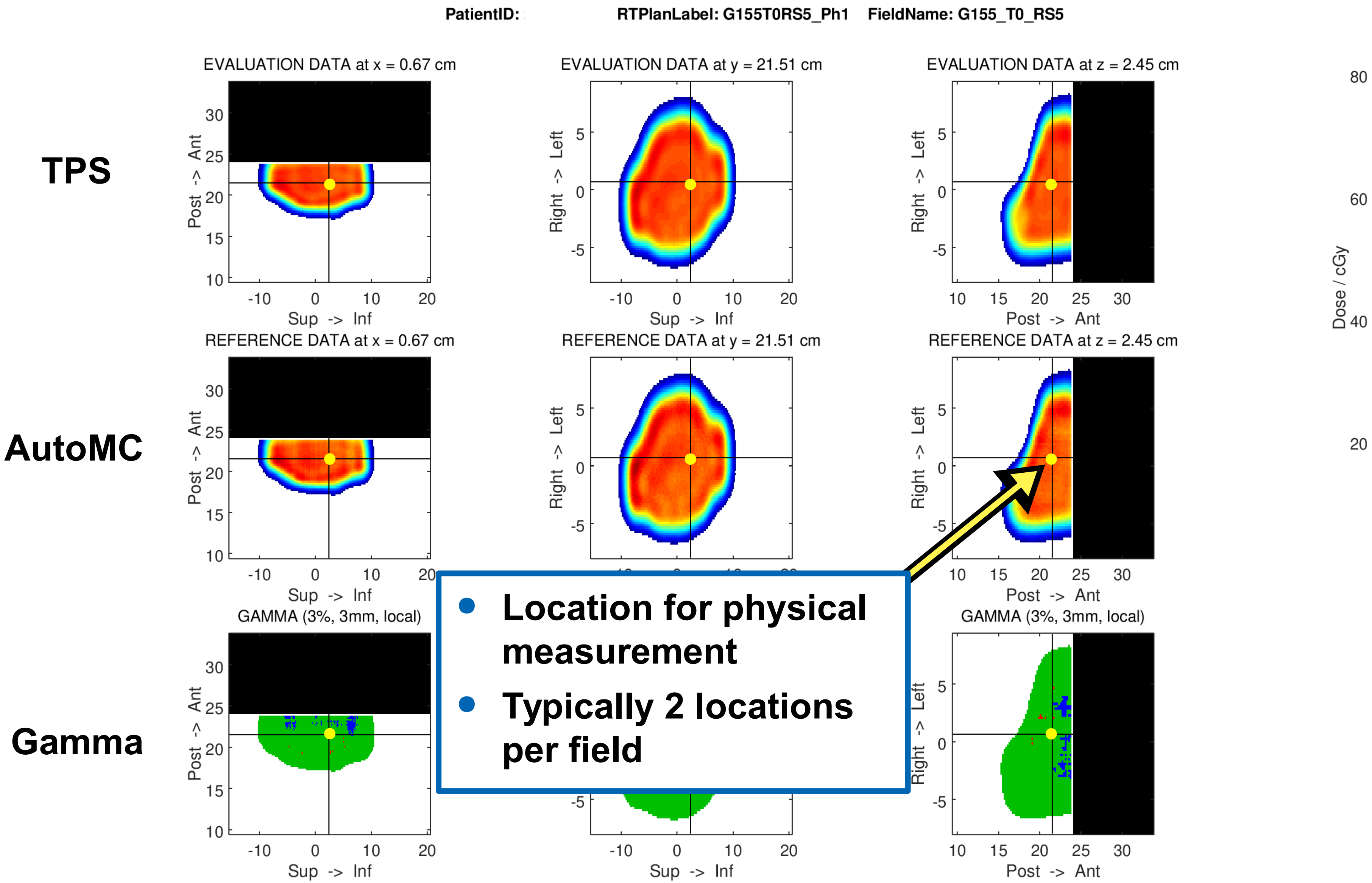


4. Physical verification: Chamber

PatientID: **RTPlanLabel: G155T0RS5_Ph1** **FieldName: G155_T0_RS5**



4. Physical verification: Chamber



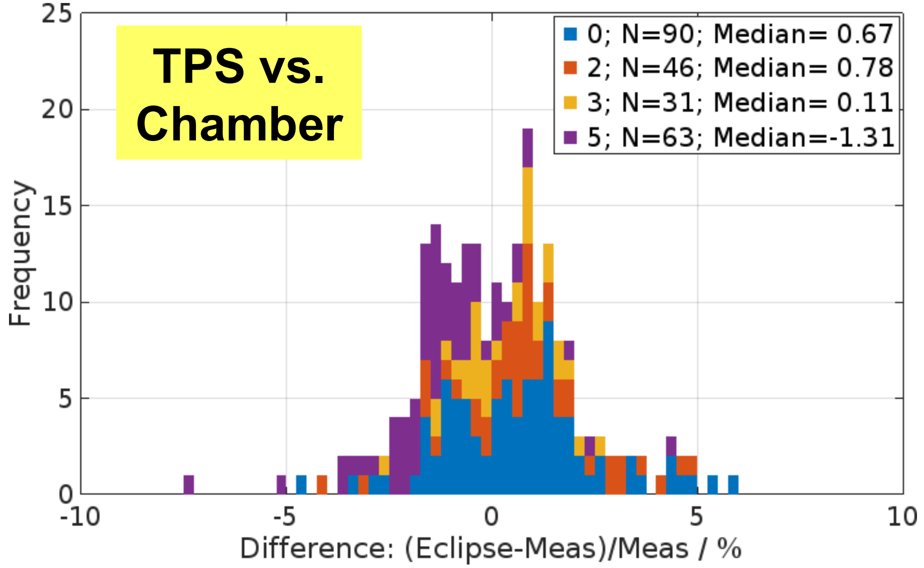
- **Location for physical measurement**
- **Typically 2 locations per field**

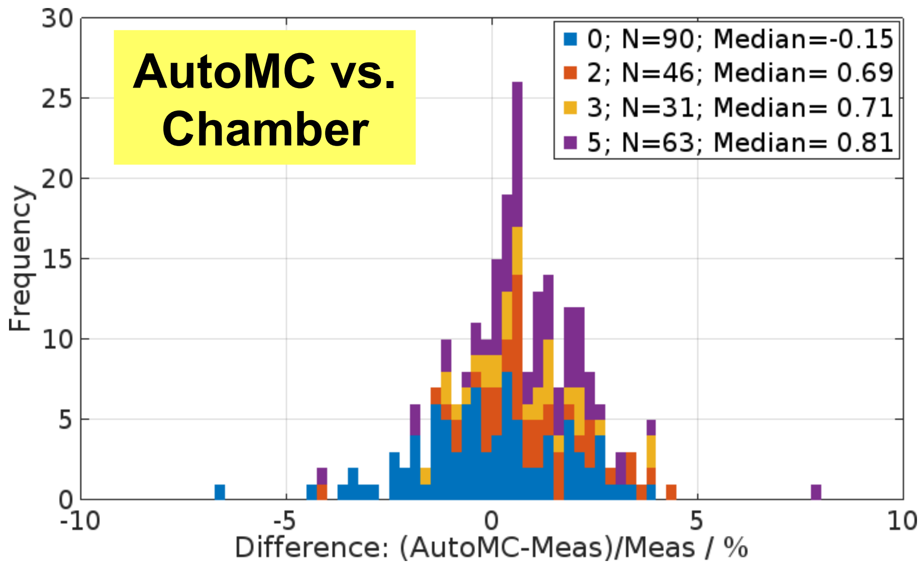
4. Dose difference: Calculated & Measured

- Patients planned to date: **44**
- Patients analysed using MC: **26**
- Fields analysed using MC: **108**
- Physical measurement locations: **230**

- TPS and measurement agree (systematically) within: **+/- 1.3%**
- MC and measurement agree (systematically) within: **+/- 0.8%**

- The spread in the data is mainly due to uncertainty in the chamber measurements.

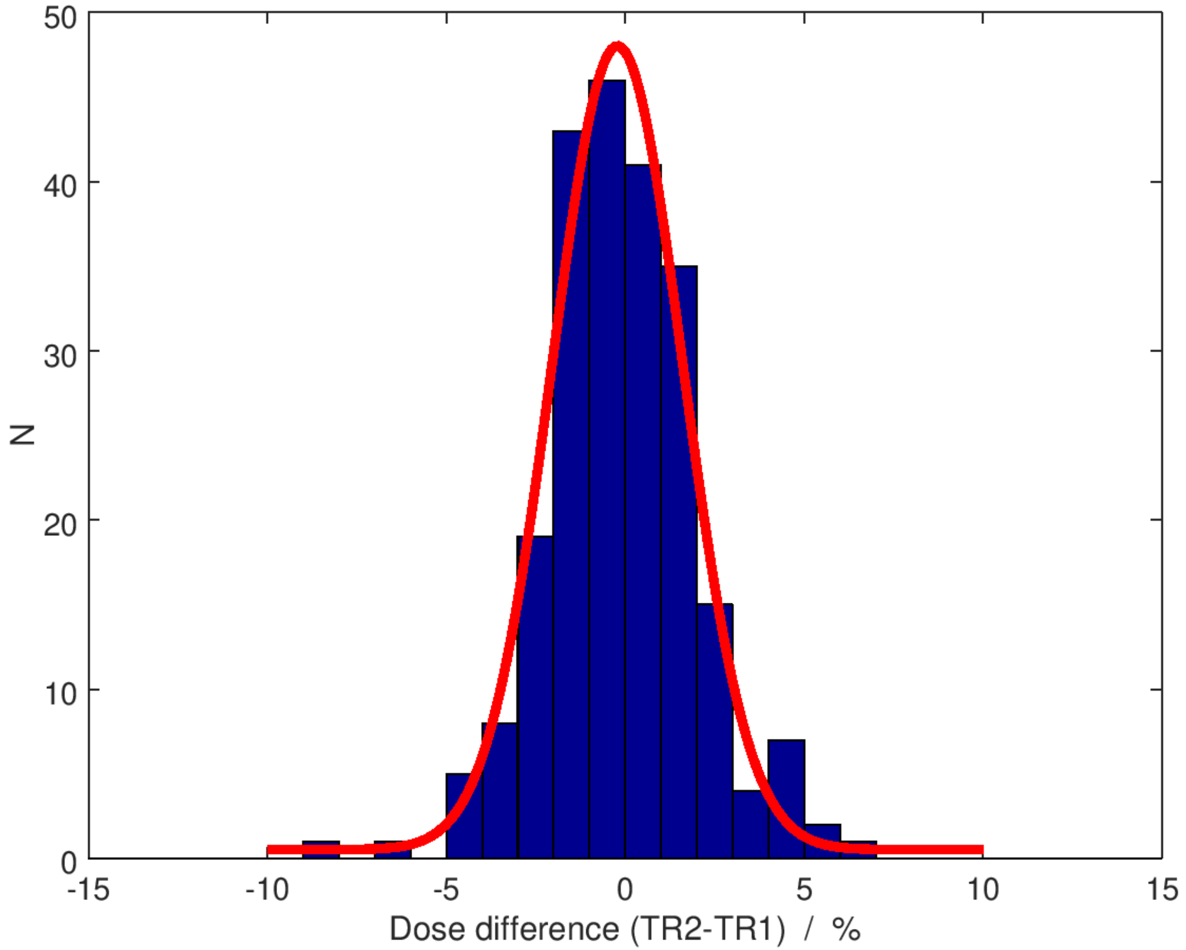




4. Chamber: Variation on repeat measurement

Number of chamber measurements:
N = 228

Gaussian fit:
σ = 1.8%



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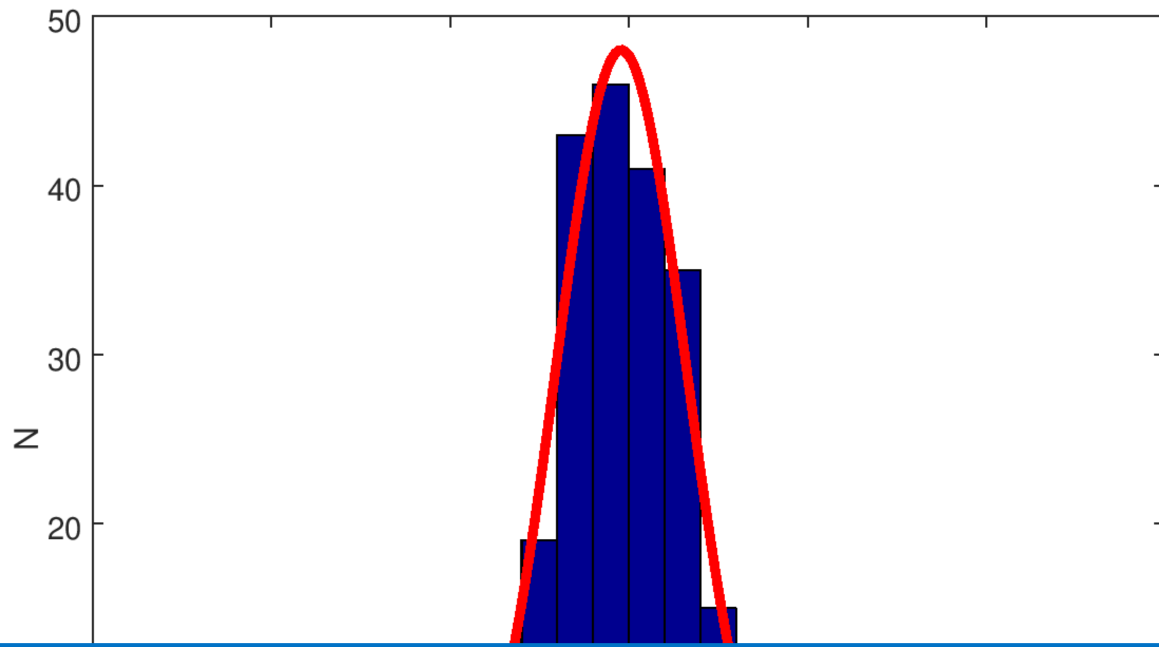


Note:

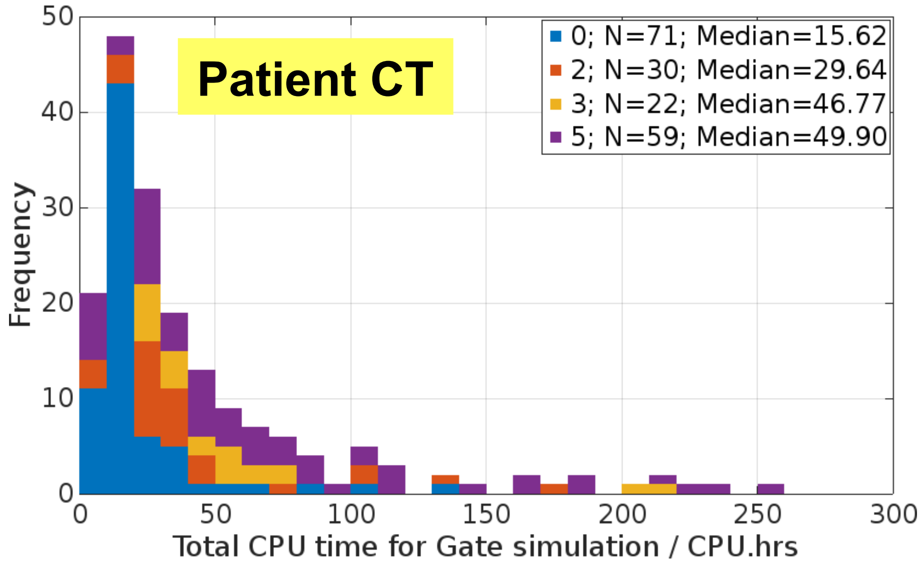
- The variation of repeated point dose measurements is typically greater in magnitude than the dose differences between TPS and MC.

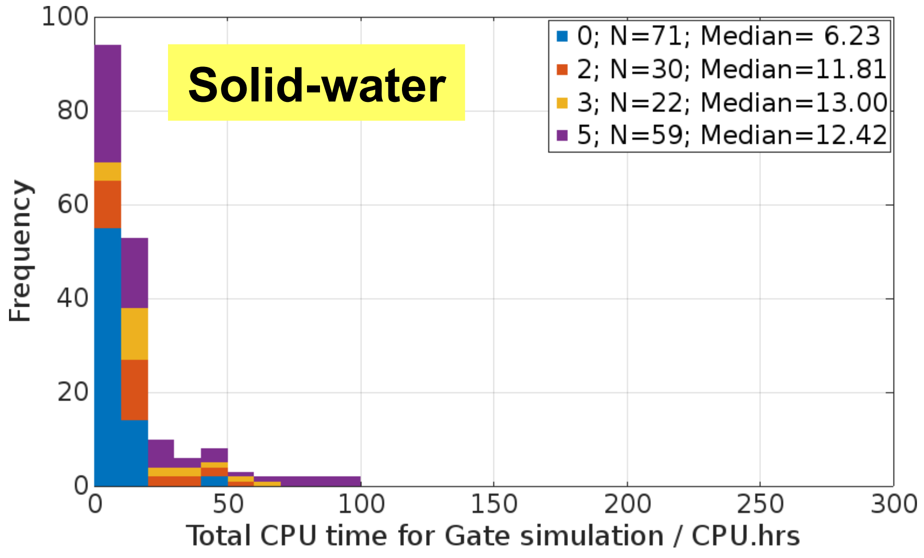
5. Other issues: Simulation time

- The number of primaries is automatically set to achieve an uncertainty of < 0.8% within the 90-100% isodose region.

- Simulation time is dependent on:
  - Target volume
  - Dose grid resolution
  - Number of energy layers
  - Relative weighting of layers
  - Pre-absorber thickness
  - Medium: Patient CT / Solidwater

- Total simulation times:
  - 0.5 – 12 hours per field
  - Suitable for overnight calculation.



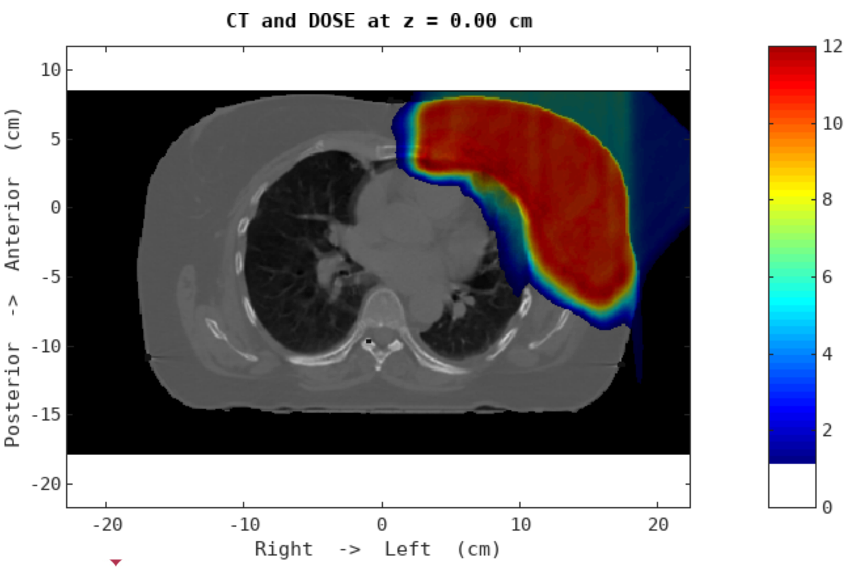


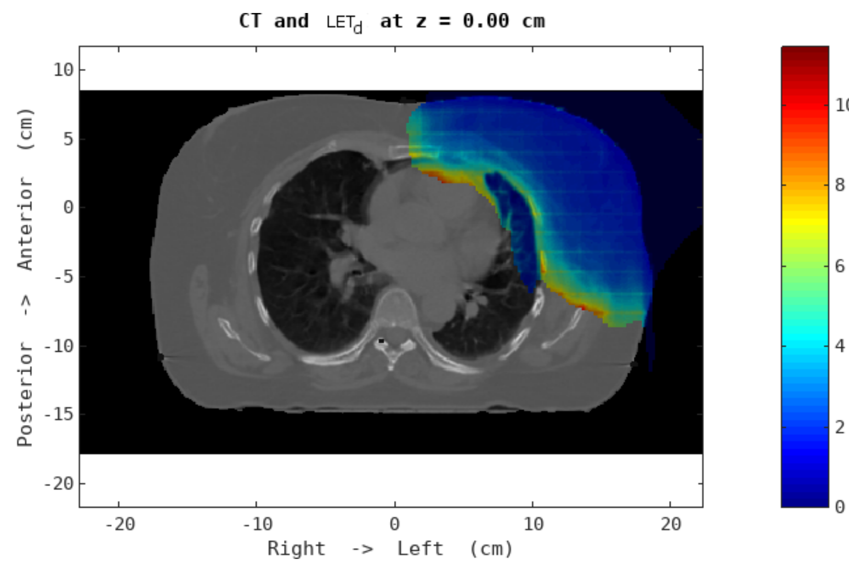
5. Other issues: LET

- LET calculation is straightforward in GATE RTion.
- Issues:
  - Which flavour of LET is most clinically relevant?
    - Track averaged / Dose averaged
    - Restricted / Unrestricted
    - LET-to-water / LET-to-medium
  - What is the sensitivity to the choice of physics list?
  - Etc.

Current interest at Christie & University of Manchester:

- Ed Smith
- Carla Winterhalter
- Nicholas Henthorn
- Tracy Underwood
- Jenny Richardson





Images courtesy of UK Breast PBT Working Group

Summary

Example of the use of GATE RTion for independent calculation of proton PBS treatment plans:

- Automation for routine clinical use.
- The same commissioning data is used to configure the beam-model and CT calibration in both TPS and MC.
- No post-commissioning correction factors are applied.

Results from first cohort of patients planned/verified at the Christie:

- Absolute dose distributions calculated in TPS and MC agree within the uncertainty of physical verification measurements.

Acknowledgements

www.opengatecollaboration.org/GateRTion

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