LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Towards EPID-based 3D in-vivo Dosimetry for Modern Radiation Therapy

Dr. Juliana Martins

juliana.martins@physik.uni-muenchen.de

7th June, 2024

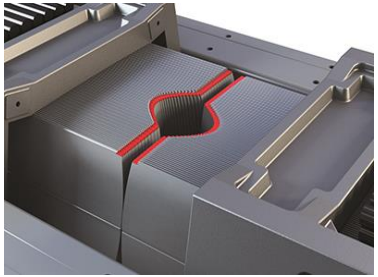
Modern Radiation Therapy?

- IMRT: Intensity Modulated Radiation Therapy
  - Photons!
  - Complex treatments with steep dose gradients
    - Different irradiation angles
    - Multi Leaf Collimators (MLC)
    - Fluence modulation of incident beam
  - Better coverage of tumor while sparing healthy tissues and organs
  - Gantry is static during irradiation
    - “Next Step”: Volumetric Arc Therapy (VMAT), continuous gantry rotation

IMRT

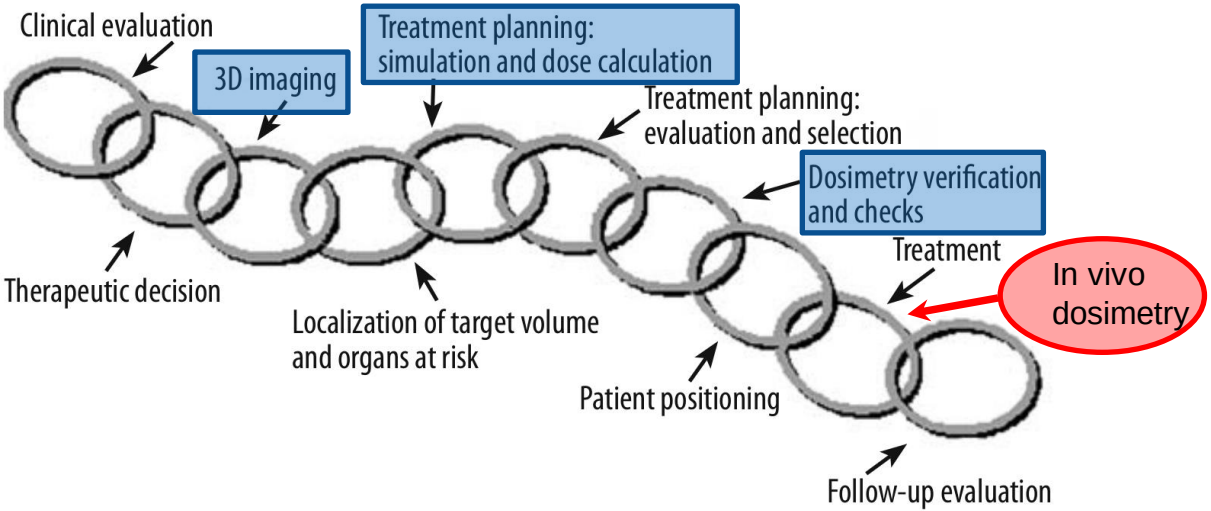
Elekta Synergy® Linac with
Elekta Agility MLC

MLC



Wolfgang Schlegel, Thomas Bortfeld, Anca L Grosu, Tinsu Pan, and Dershan Luo. New technologies in radiation oncology. *Journal of Nuclear Medicine*, 2008
Thomas Bortfeld, Wilfried Neve, Rupert Schmidt-Ullrich, and David E Wazer. I*mage-guided IMRT*. Springer, 2006.

In-vivo Dosimetry



W. Schlegel, T. Bortfeld, A.-L. Grosu, 2006

Pre-treatment vs in-vivo dosimetry

Pre-treatment verification

Potential errors:

- Dose miscalculation (TPS beam model)
- Machine related errors:
  - Data transfer miscommunication
  - Beam flatness, symmetry, intensity rate
  - MLC malfunctioning, collimator, gantry…

Different methods are well established in clinical routine (EPID)

In-vivo dosimetry

Potential errors:

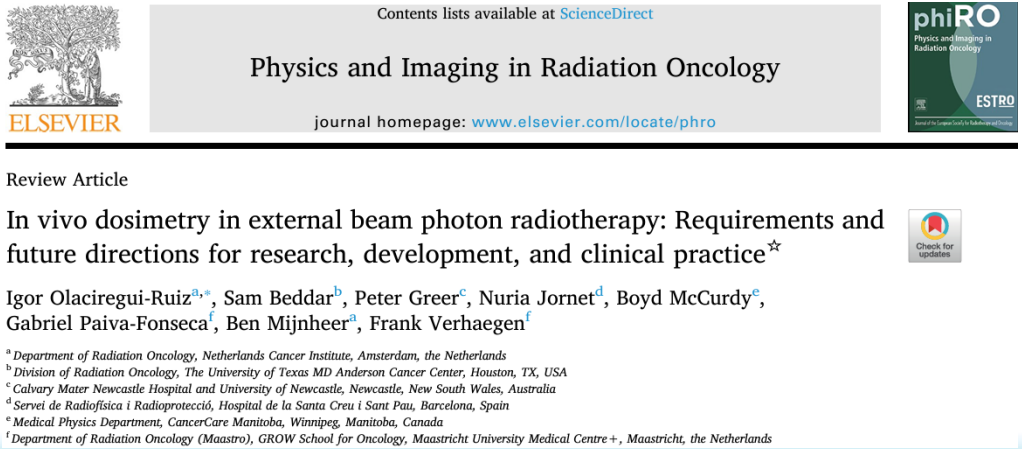
- Same as in pre-treatment verification (but during treatment)
- Discrepancies in patient geometry
  - Positioning errors
  - Anatomical changes (targets, OARs)
  - Bolus material…

Used in (some) clinics (EPID), but not well established in general

In-vivo dosimetry: approaches

- Point detectors at patient skin
  - Time consuming (evaluation), point dose values
- Point detectos inserted in target/OARs
  - Time consuming, invasive, uncertainty (positioning, changes in anatomy)
- Film dosimetry
  - Surface dose, 2D
- EPID!
  - In-air acquisitions
  - Dose-in-water
  - Corrections

More information



ELSEVIER

Contents lists available at ScienceDirect

Physics and Imaging in Radiation Oncology

journal homepage: www.elsevier.com/locate/phro

phiRO Physics and Imaging in Radiation Oncology ESTRO

Review Article

In vivo dosimetry in external beam photon radiotherapy: Requirements and future directions for research, development, and clinical practice☆

Igor Olaciregui-Ruiz[a,*], Sam Beddar[b], Peter Greer[c], Nuria Jornet[d], Boyd McCurdy[e], Gabriel Paiva-Fonseca[f], Ben Mijnheer[a], Frank Verhaegen[f]

[a] Department of Radiation Oncology, Netherlands Cancer Institute, Amsterdam, the Netherlands
[b] Division of Radiation Oncology, The University of Texas MD Anderson Cancer Center, Houston, TX, USA
[c] Calvary Mater Newcastle Hospital and University of Newcastle, Newcastle, New South Wales, Australia
[d] Servei de Radiofísica i Radioprotecció, Hospital de la Santa Creu i Sant Pau, Barcelona, Spain
[e] Medical Physics Department, CancerCare Manitoba, Winnipeg, Manitoba, Canada
[f] Department of Radiation Oncology (Maastro), GROW School for Oncology, Maastricht University Medical Centre+, Maastricht, the Netherlands

EPID?

- Electronic Portal Imaging Device
  - Amorphous silicon (a-Si) EPID
- 2D panel detector installed in most clinical linear accelerators
- Primarily developed for patient positioning verification
  - Sime signal reaches the EPID! Dose information?
- Interesting dosimetric properties
  - Investigation of their use for dose measurements

  - Sub-millimeter spatial resolution
  - Temporal resolution in the order of ms
  - Approximated linear response to radiation
  - Digital and real time readout
  - Large sensitive area

Kirby, M. C., and A. G. Glendinning. "Developments in electronic portal imaging systems." *The British journal of radiology* 2006
Van Elmpt, Wouter, et al. "A literature review of electronic portal imaging for radiotherapy dosimetry." *Radiotherapy and oncology* 2008

a-Si EPID

- Flat panel detector
- Scintillation layer connected to a pixelated photodiode array based on amorphous silicon (a-Si) semiconductors
- 1-mm thick copper build-up plate placed on top of the scintillator
- All enclosed in a low-density plastic cover and connected to a read-out system

EPID Model (Elekta iView GT™)	PelkinElmer XRD 1640
Scintillator screen	CsI
Pixel number	1024 x 1024
Active area (cm^2)	41 x 41
Pixel size (mm)	0.4
Max. frame rate (fps)	3.5
SSD (cm)	160
Max. Field size (cm^2)	25 x 25

Ross I Berbeco. *Beam's Eye View Imaging in Radiation Oncology*. CRC Press, 2017

In-vivo dosimetry: requirements?

An optimal methodology for in-vivo dosimetry should be accurate and fast, providing reliable estimates of the three-dimensional dose delivered to the patient within seconds, and should not increase the workload on the clinical staff.

- Possible solution: EPID-based 3D in-vivo dosimetry exploring the benefits from both Monte Carlo methods (accuracy) and Deep Convolutional Neural Networks (efficiency)

Motivation and Goal

- Intensity Modulated Radiation Therapy (IMRT)
  - Complex treatments with steep dose gradients
  - Better coverage of tumor while sparing healthy tissues and organs

- EPID-based 3D in-vivo dosimetry exploring the benefits from both Monte Carlo methods (accuracy) and Deep Convolutional Neural Networks (efficiency)
  - Deep Dose Estimation (DDE)[1]

- Train the DDE to predict the dose distribution inside the patient
  - Input: patient CT and first-order dose approximation (FOD), reconstructed from EPID signal
  - Target: MC-simulated dose distribution

[1] Maier, Joscha, et al. "Real-time patient-specific CT dose estimation using a deep convolutional neural network." *2018*

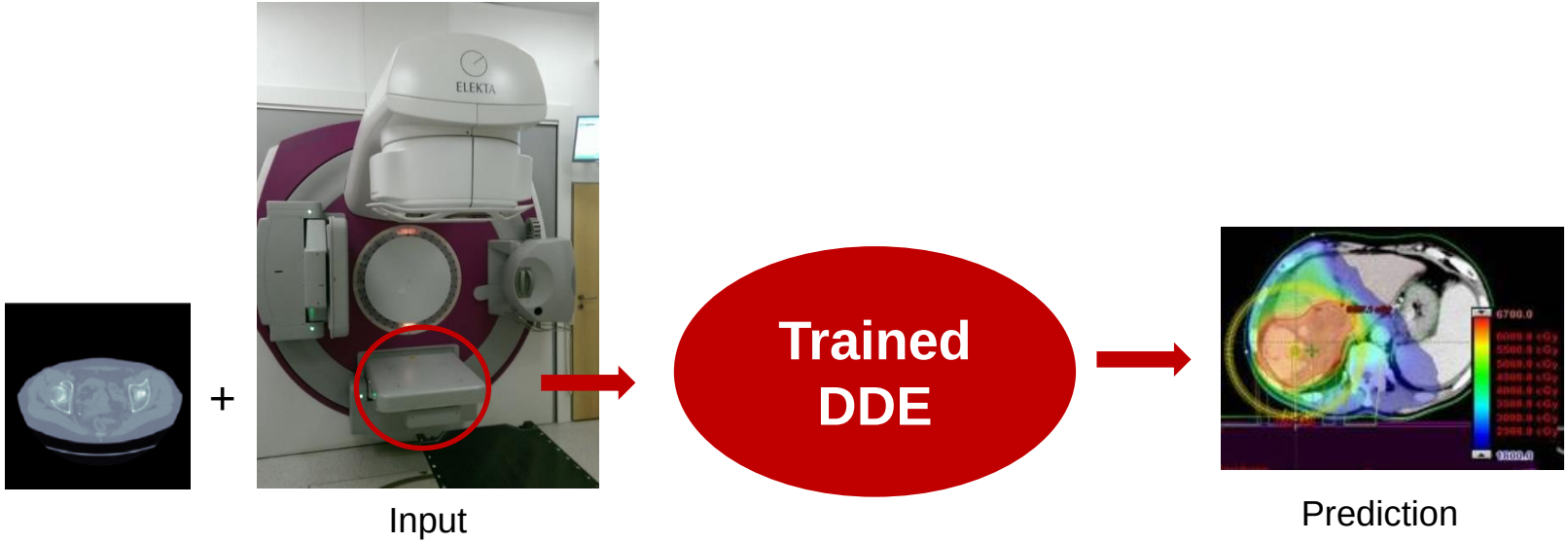
DDE: Deep Dose Estimation

- Originaly developed to predict patient-specific dose distribution for radiological Computed Tomography (CT) acquisition
  - Input:
    - Patient CT image
    - 3D dose approximation (First-order dose approximation – FOD)
  - Target:
    - MC simulated dose distributions

- Extend the DDE to radiotherapy as a potential method for EPID-based in vivo dosimetry
  - Input:
    - Patient CT image
    - 3D First-order Dose Approximation (FOD) (reconstructed from 2D EPID signals)
  - Target: MC simulated dose distributions from step-and-shoot prostate IMRT plans
    - Accurate Dose Distribution (ADD)

[1] Maier, Joscha, et al. "Real-time patient-specific CT dose estimation using a deep convolutional neural network." *2018*

DDE to Radiotherapy



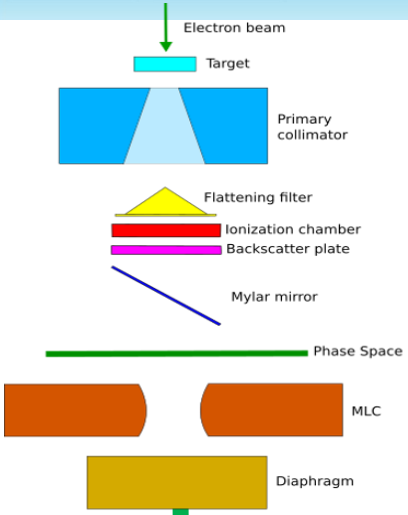
Input

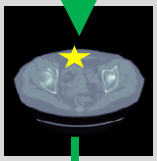
Prediction

Quality of Prediction depends on quality of the input data used for training the network

Accurate and reliable Monte Carlo Model of the clinical LINAC

Methods





3D Accurate Dose Distribution (ADD)

2D EPID signal (transmitted/attenuated)

In-house validated Geant4 MC model of a clinical linear accelerator*

3D First-order dose approximation (FOD)

$$FOD_d(Gy) = D_{w,d} \cdot \left(\frac{r_d}{r_{EPID}}\right)^{-2} \cdot e^{(\mu_{w,E} \cdot L)}$$

$$L = Radiological\ path\ length$$

*Elekta Synergy® coupled to Elekta Agility™ multi-leaf collimator

Methods

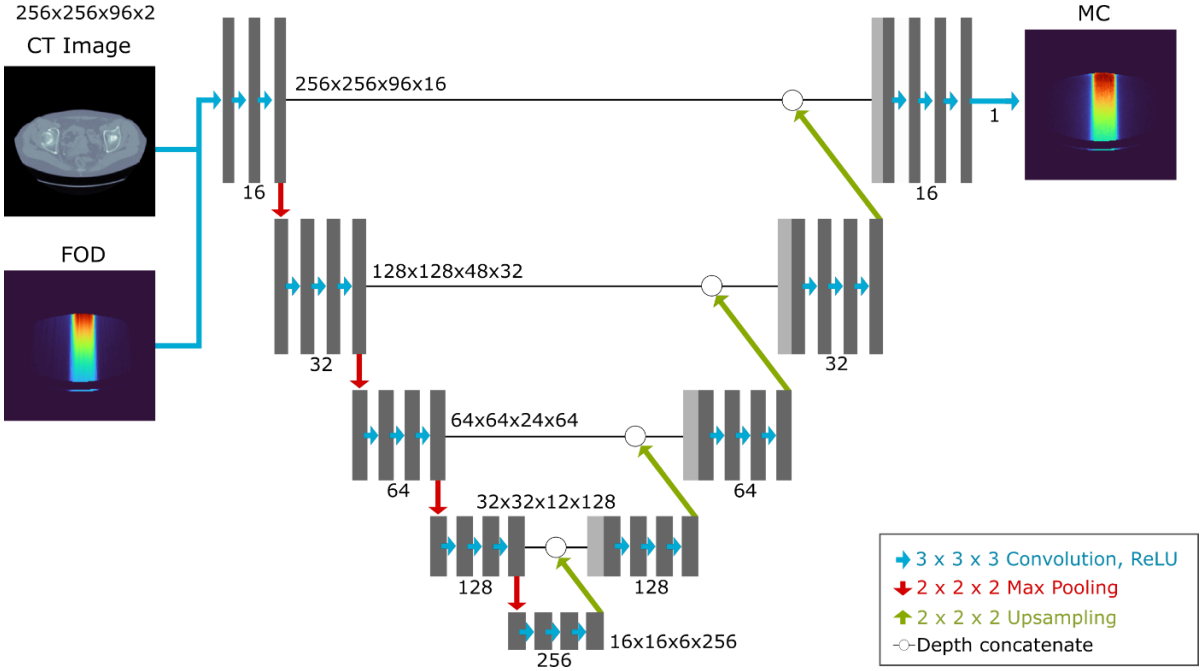
- 2 prostate IMRT clinical plans
  - 125 control points (CP)
  - All fields at simulated with gantry at 0˚ (antero-posterior)
- 83 patient pelvic CT scans
- Per patient: 3 unique fields (CP) + 4 linear combination
  - 7 fields per patient, 581 fields in total
  - 581 different ADD-FOD pairs

Training set: 67 pts. (469 fields)
Test set: 16 pts. (112 fields)

- Additional dataset simulated with gantry at 90˚ (“Lateral set”)
  - 8 different patient CTs, 8 different fields → 8 ADD-FOD pairs
  - Check the performance at different irradiation angles (left-right)

Methods

DDE: modified 3D U-net[2] architecture.



- 500 Epochs
- 47 Hours (Nvidia Quadro P5000 GPU)
- Mean absolute percentage error as loss function

[2]O. Ronneberger, et al. “U-Net: Convolutional Networks for Biomedical Image Segmentation”, 2015.

Evaluation

After the training process:

- Evaluate the performance of the trained DDE in predicting dose distributions with MC-like accuracy
  - ADD vs DDEP (DDE predictions)
- Assess the improvement obtained with the DDE, with respect to the input
  - FOD vs ADD
- Test set: evaluate the performance of the trained DDE to new, but similar, data
- Lateral set: new data from a different irradiation angle (unseen during training process)

Gamma Index Evaluation

- Quantitative method to compare two different dose distributions, widely used in radiotherapy
  - Reference distribution (RD) vs Evaluated distribution (ED)

- 2 criteria:
  - Maximum dose difference (DD, 3%)
  - Distance-to-agreement (DTA, 2 mm)
  - DD and DTA define a region of interest (ROI)

Low D et al. A technique for the quantitative evaluation of dose distributions. *Medical Physics* 1998.

Gamma Index Evaluation

- Each voxel of the ED is compared to all voxels in the RD located inside the ROI, the lowest Γ is considered the best match:

$$\Gamma(\vec{r}_{ref}, \vec{r}_{ev}) = \sqrt{\frac{|\vec{r}_{ev} - \vec{r}_{ref}|}{DTA^2} + \frac{D_{ev}(\vec{r}_{ev}) - D_{ref}(\vec{r}_{ref})}{DD^2}}$$

$$\gamma(\vec{r}_{ref}) = min\{\Gamma(\vec{r}_{ref}, \vec{r}_{ev})\} \forall \{\vec{r}_{ev}\}$$

- γ value was multiplied by the sign of the dose difference between the evaluated and reference voxels, to indicate an underdosage ($\gamma < 0$) or oversosage ($\gamma > 0$)

Mark Podesta, Lucas CGG Persoon, and Frank Verhaegen. A novel time dependent gamma evaluation function for dynamic 2d and 3d dose distributions. *Physics in Medicine & Biology* 2014.

Gamma Index Evaluation

- Define a pass/fail criteria for every evaluated voxel

$$|\gamma(\vec{r}_{ref})| \leq 1, evaluated\ voxel\ passes$$

$$|\gamma(\vec{r}_{ref})| > 1, evaluated\ voxel\ fails$$

- The passing rate (percentage of voxels passing the gamma evaluation) reflects the agreement between evaluated and reference dose distributions

Results and Discussions

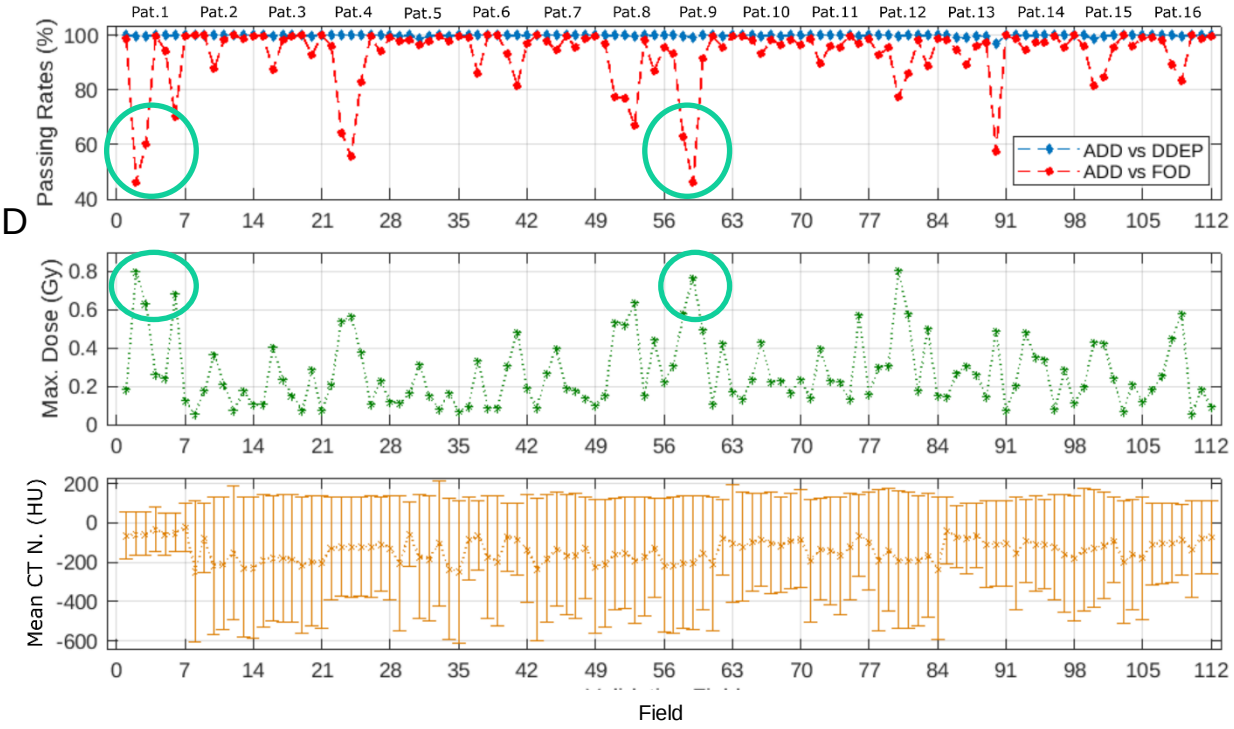
Gamma passing rates for test set (0˚)

- ADD vs FOD: ≥ 46 %
- ADD vs DDEP ≥ 97 %

Clear correlation to max. dose in ADD

- Linearly-combined plans

No correlation to mean CT number,
no special feature in patient CT
(ex. Gender, metal inserts, couch…)



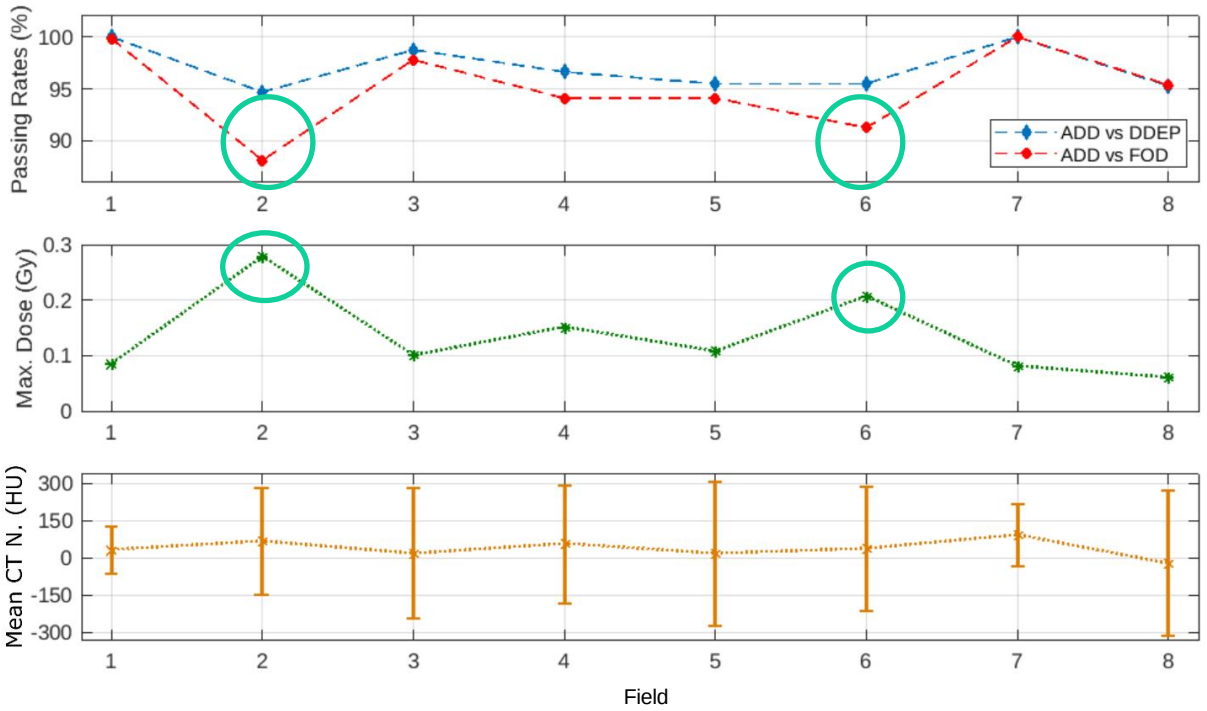
Results and Discussions

Gamma passing rates for lateral set (90˚)

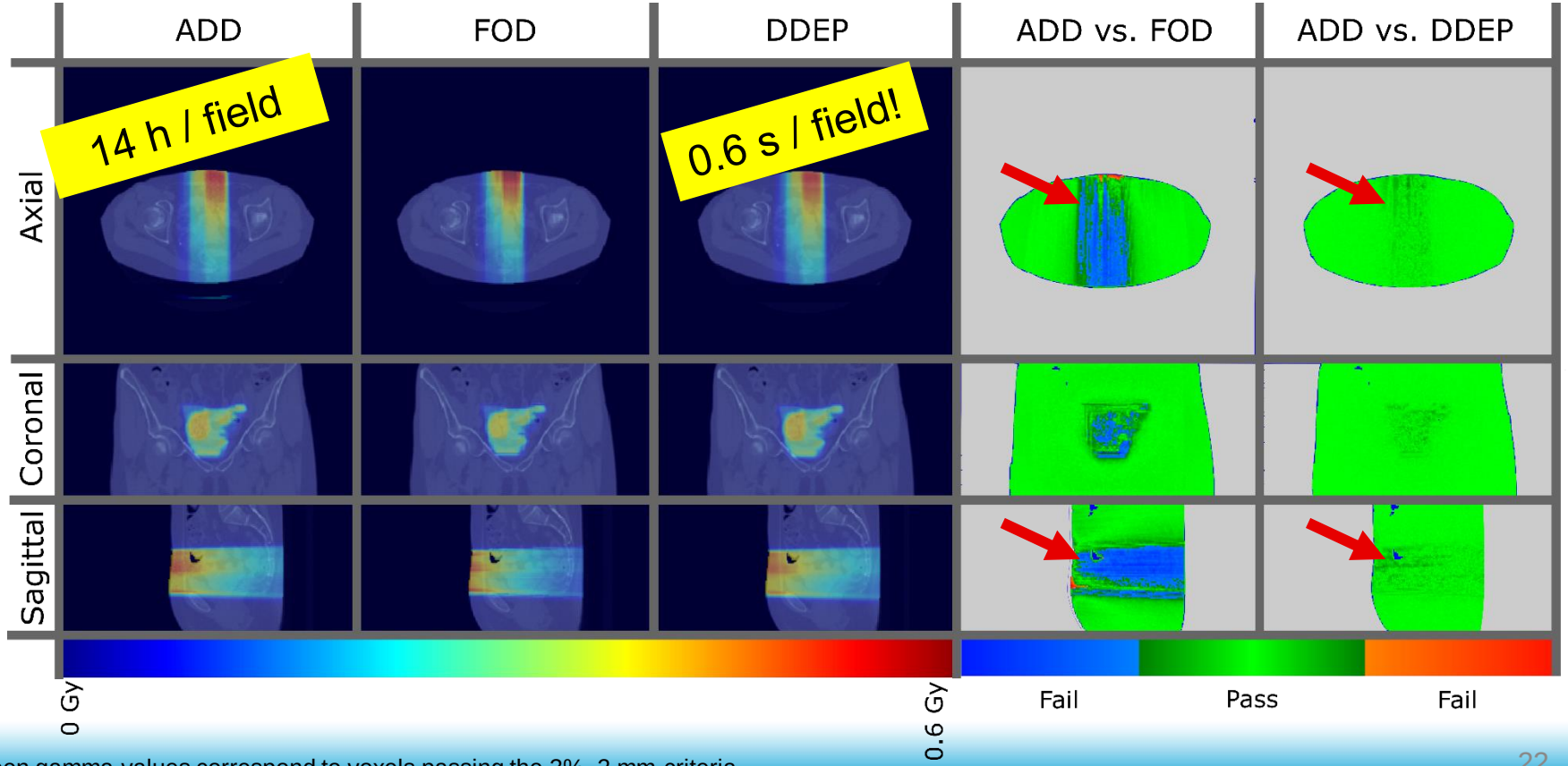
- ADD vs FOD ≥ 88 %
- ADD vs DDEP: ≥ 95 %

Clear correlation to max. dose in ADD

No correlation to mean CT number,
no special feature in patient CT
(ex. Gender, metal inserts, couch…)

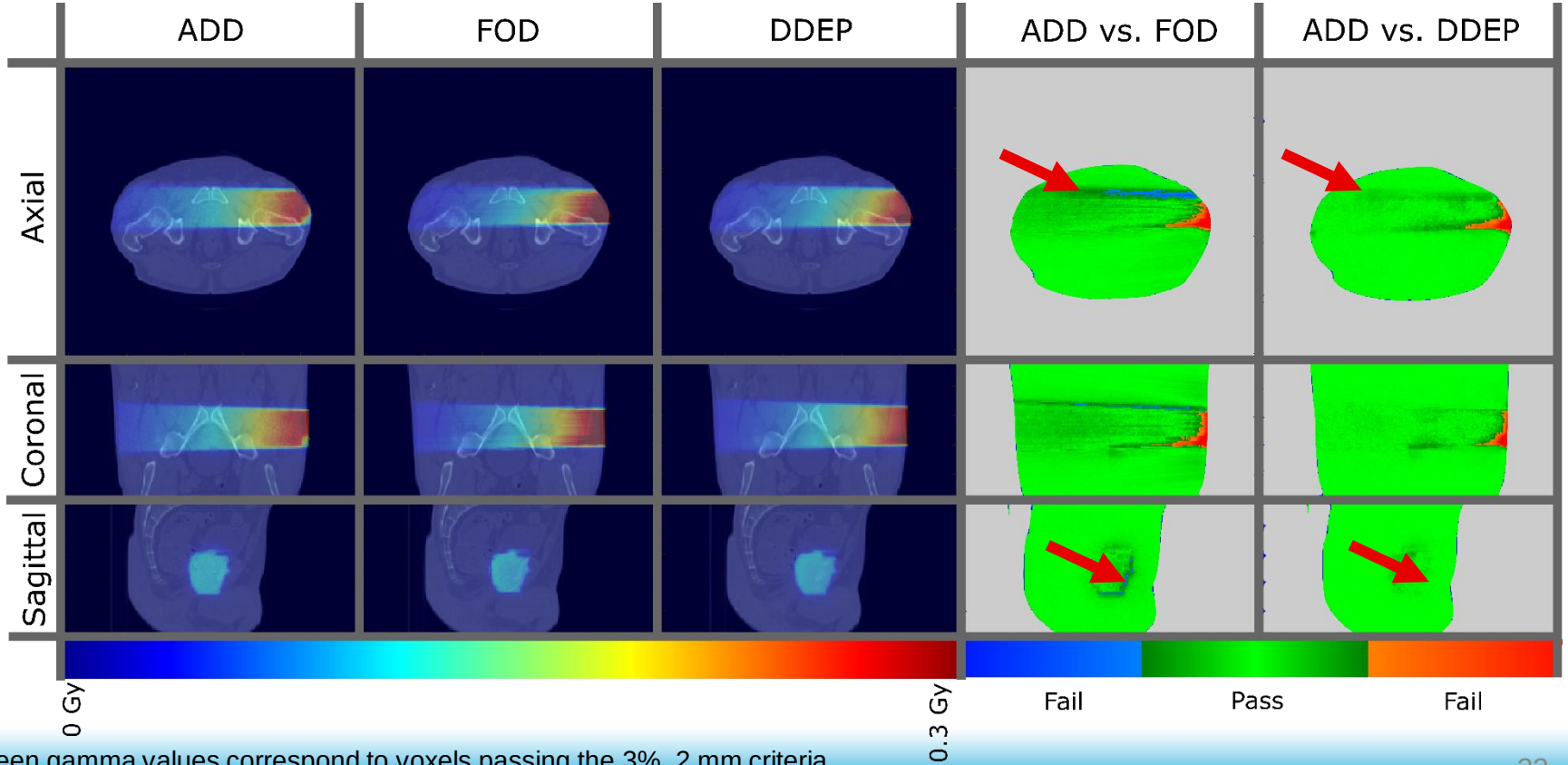


Results and Discussions



Green gamma values correspond to voxels passing the 3%, 2 mm criteria.

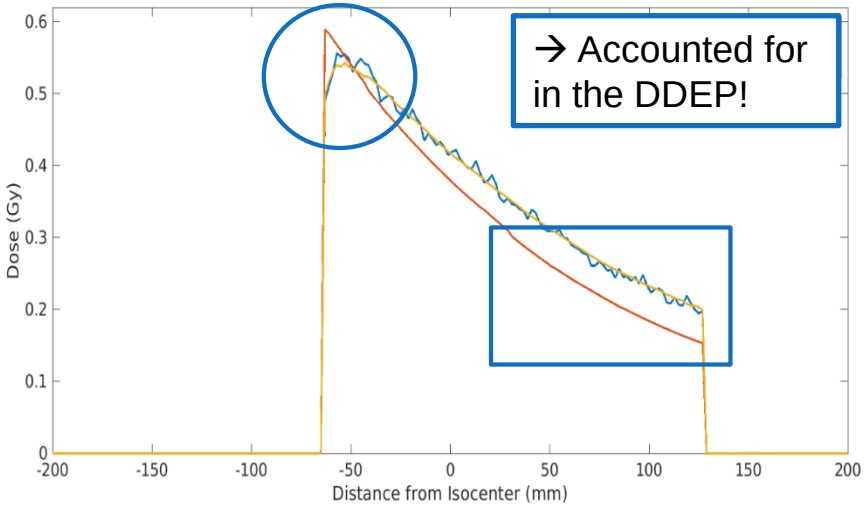
Results and Discussions



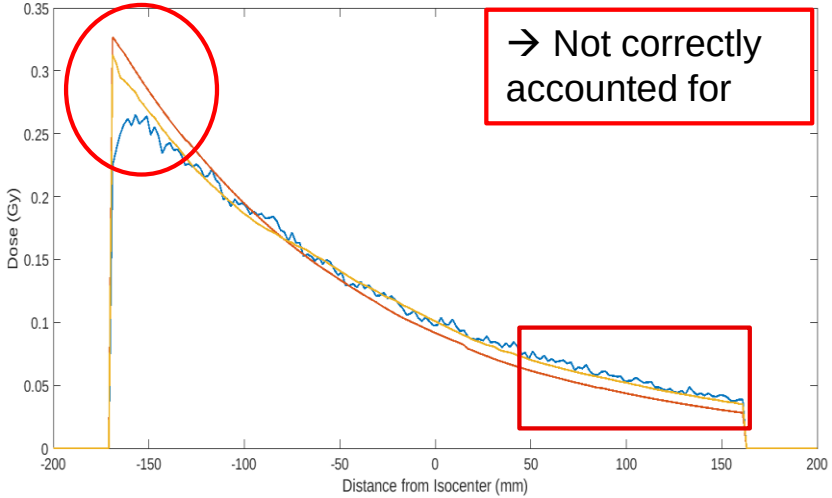
Green gamma values correspond to voxels passing the 3%, 2 mm criteria.

Results and Discussions

Test set 0˚



Lateral set 90˚



FOD does not consider build-up effect and scattering (but well described by Monte Carlo)

$$FOD_d(Gy) = D_{w,d} \cdot \left(\frac{r_d}{r_{EPID}}\right)^{-2} \cdot e^{(\mu_{w,E} \cdot L)}$$

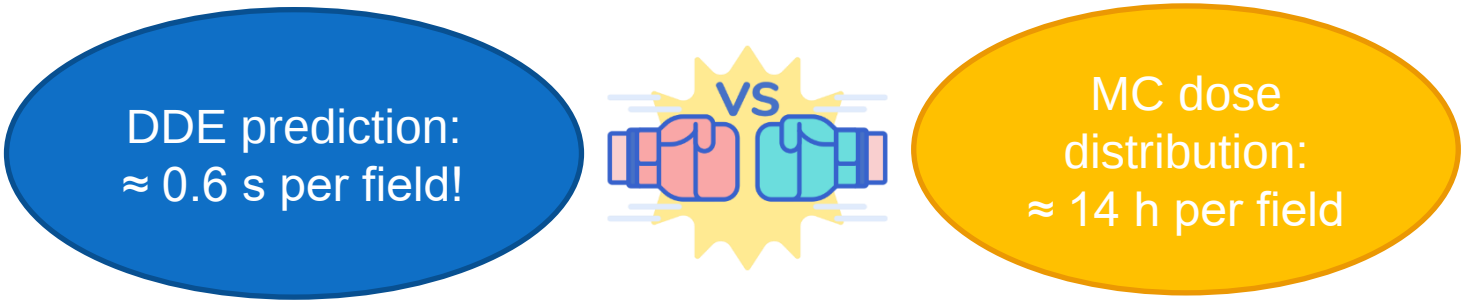
Results and Discussions

- Clear improvements on the γ passing rates for the test set
  - Trained DDE properly accouned for build-up and scatter effects, yielding dose distributions comparable to the target ADD (MC)
  - Trained network performed well in unseen data
    - Not overfitted to training dataset

- For lateral set:
  - DDEP approximates to ADD, but improvements are less pronounced
  - Justified by the absence of simulations at 90˚ in the dataset used for training
  - The performance of the DDE would certainly benefit from the inclusion of irradiation from different directions and different anatomical regions in the training process.

Results and Discussions: Time

- DDE clearly outperforms Monte Carlo simulations
- DDE training: 47 hours in an Nvidia Quadro P5000 GPU (“old” model)



→ Meaningful reduction on training and prediction time if implemented in newest GPU models

Results and Discussions

- ADD training targets are Monte Carlo simulations, simulated as dose-to-medium distributions inside patient CTs
  - Properly accounts for inhomogeneities in the volume
- Network learns how to map the FOD (dose-to-water) into dose-to-medium
  - DDEPs are also given in dose to medium!
- Monte Carlo simulations: most time consuming part of the method
  - Is accurate and independent
  - Simulations with good statistics can take long (specially in CPUs…)
  - Linac model should be accurate (geometric information not easily available)
  - Possible solution: clinical TPS (corrections may apply)

Conclusions and outlook

An optimal methodology for in-vivo dosimetry should be accurate and fast, providing reliable estimates of the three-dimensional dose delivered to the patient within seconds, and should not increase the workload on the clinical staff.

- After training (~47 hours), DDE predicts dose distributions within seconds

- DDE predictions are comparable to target ADD: Monte-Carlo like accuracy

- No increase on patient time-slot and workload on clinical staff (with respect to other in-vivo methods proposed)

Conclusions and outlook

- To improve results and extend the method: increase dataset!
  - Different gantry angles
  - Different anatomical regions
  - Different treatment plans and beam energy

- To potentially overcome the gap to clinical use: measured data

- Usage of CBCT?
  - Acquired right before patient treatment → towards real time in-vivo dosimetry!

- DDE extended to RT, but originally for CT
  - Potential to extend to dose estimation throughout the entire RT chain
  - Risk assessment and late effects.

Acknowledgments

- Ludwig-Maximilians-Universität München, Germany
  - Dr. Gianoli, Dr. A. Alhazmi, Dr. S. Veloza, Dr. G. Dedes, Prof. Dr. Katia Parodi
- University Hospital, LMU Munich, Germany
  - S. Neppl, Dr. M. Reiner, Prof. Dr. C. Belka, Prof. Dr. G. Laundry
- German Cancer Research Center (DKFZ), Germany
  - Dr. J. Maier, Prof. Dr. M. Kachelriess
- Department of Radiation Oncology, Maastricht University
  - Dr. M. Podesta

Thank you for your attention!