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AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE
AGH UNIVERSITY OF KRAKOW

Narodowy Instytut Onkologii
im. Marii Skłodowskiej-Curie
Państwowy Instytut Badawczy
Oddział w Krakowie

Dose 3DF

Up-scaling for measuring the spatial distribution of radiation dose for applications in the preparation of individual patient treatment plans

Bartłomiej Rachwał
on behalf of **Dose-3D-Future** Collaboration
AGH University of Krakow

2nd International Workshop on Machine Learning and Quantum Computing Applications in Medicine and Physics

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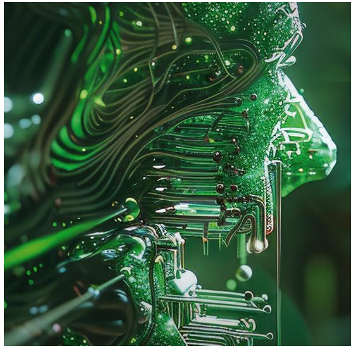


Outline

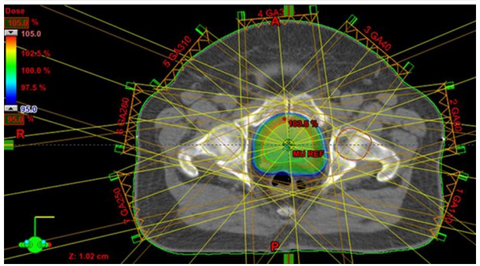
- Project motivation
- Dose3D detector system in the context of TPS
- Geant4-based MC simulation platform
- Super-resolution, U-net and it’s modifications
- Up-scaling for measuring the spatial distribution of radiation dose

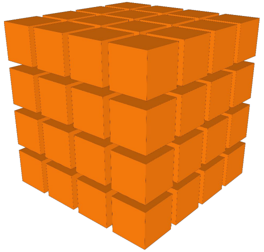
Project motivation

For the **X-ray based therapies full 3D dose measurements** require external equipment for measurement and do not provide real-time information [1].

↪ The better is our understanding of dose deposition in tissue, the more accurate patient treatment planning can be.

↪ Chances of the patient’s full recovery are increased, and potential excessive neighbouring tissue damage is reduced.



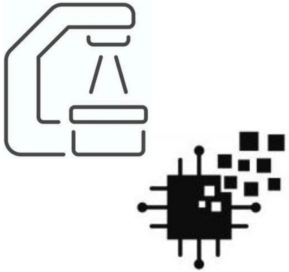


Dose-3D detector [2] aims to measure radiation dose with spatial granulation and in real-time!

[1] Descriptions of an active 3D detector for radiation therapy exist, but these are dedicated for proton irradiations: M. Sądel, et al., Sensors (2021) http://dx.doi.org/10.3390/s21186015

[2]. M. Kopeć, et al. *A reconfigurable detector for measuring the spatial distribution of radiation dose for applications in the preparation of individual patient treatment plans.* Nuclear Inst. and Methods in Physics Research, A 1048 (2023) 167937

System building blocks



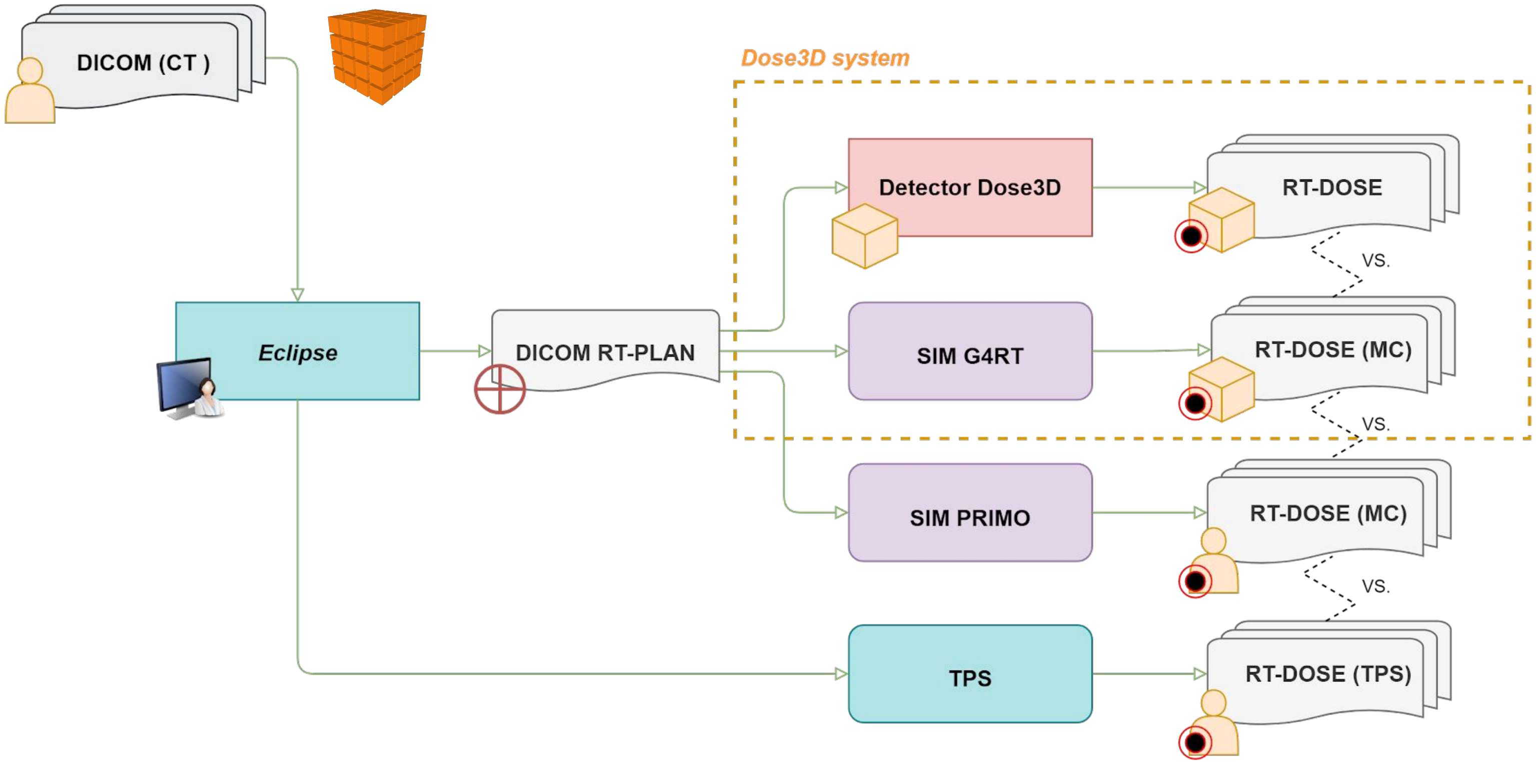
Detection head allowing for changes in geometry dependant on patient's needs

- Reconfigurable and Flexible detector geometry
- Up to couple thousand of cells of about 1 cc
- Tissue equivalent scintillator
- Scalable Data Acquisition (DAQ) system supporting reconfigurability

High-level software using ML techniques to analyse medical imaging and generate detector geometry for the configuration and simulations

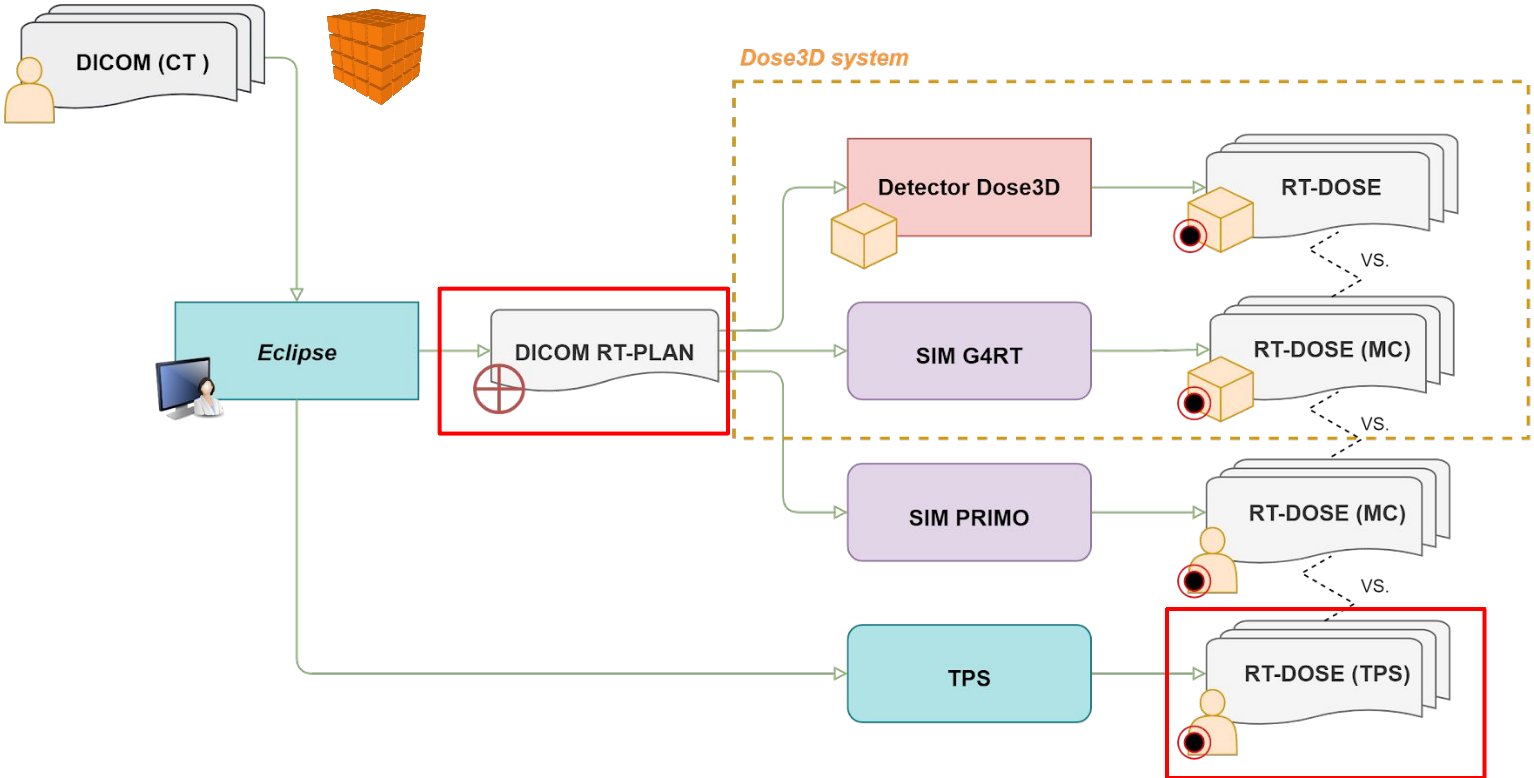
- Treatment (dose in 3D) simulation
- Therapy planning
- <u>Standalone simulator platform</u> based on Geant4 engine
    - easy to use in medical physicist community (easy deployment)
    - standard analysis tools included

Treatment Planning System data flow



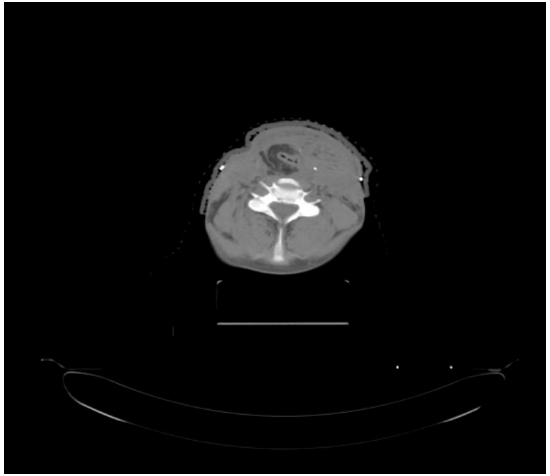
Treatment Planning System data flow

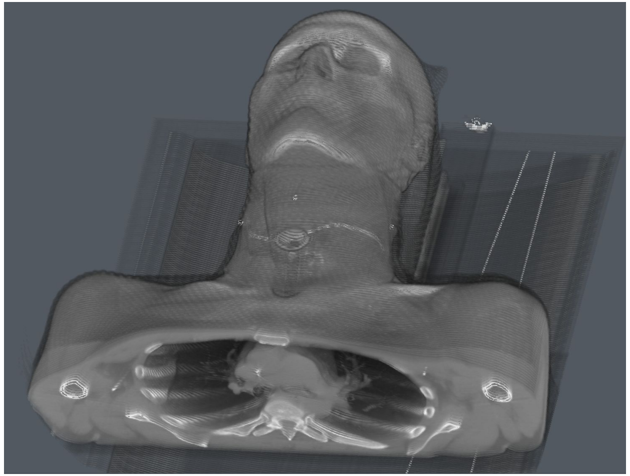
RT-Plan & RT-Dose



Treatment **P**lanning **S**ystem data flow

The patient: DICOM-**CT**





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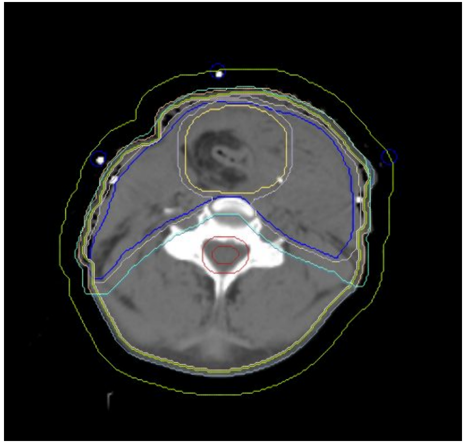
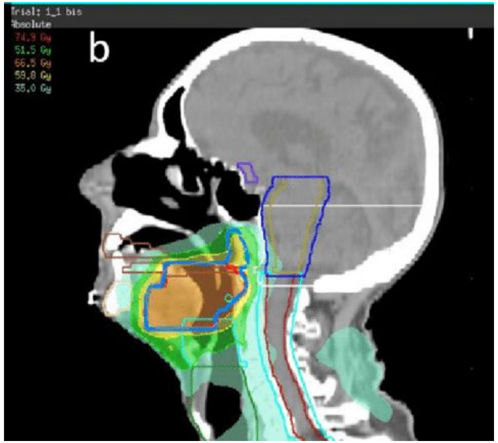
Treatment **P**lanning **S**ystem data flow

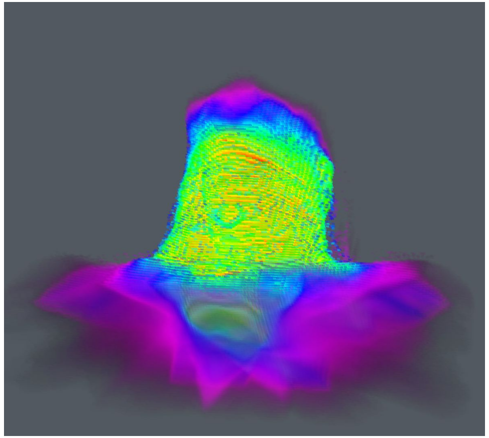
The patient: RT-**Struct**, RT-**Plan**, RT-**Dose**



Exported with Aliza MS for anonymized patient



https://doi.org/10.1007/978-3-031-23175-9_8

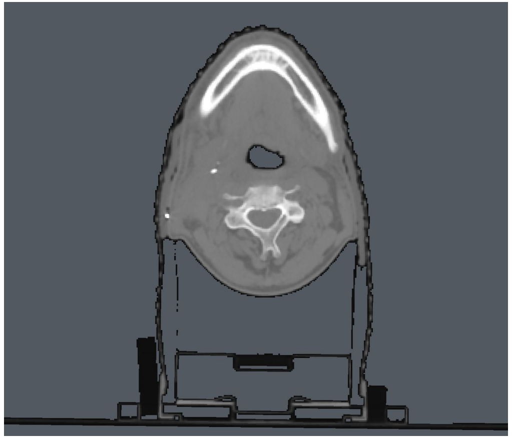


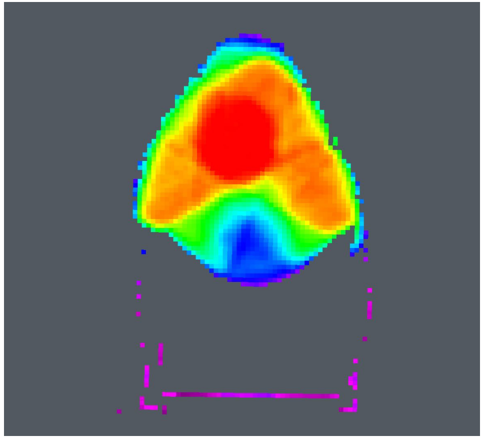
Exported with Aliza MS for anonymized patient

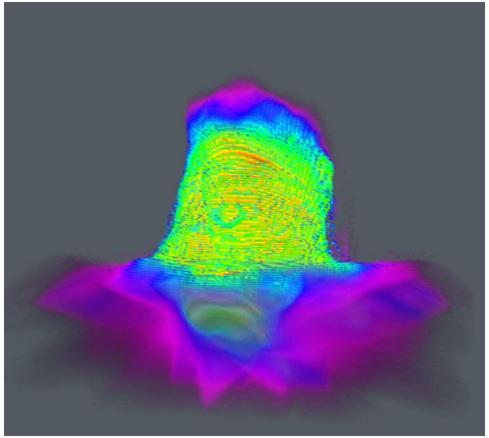
Treatment **P**lanning **S**ystem data flow

The patient: DICOM-**CT**, RT-**Dose**

single slice







CT images commonly have a resolution ~2 mm in the axial plane (slice thickness). The in-plane resolution, which refers to the size of the individual pixels or voxels within the image:
~ 1 mm x 1 mm

Common voxel sizes for RT-Dose data
~2.5 mm per side

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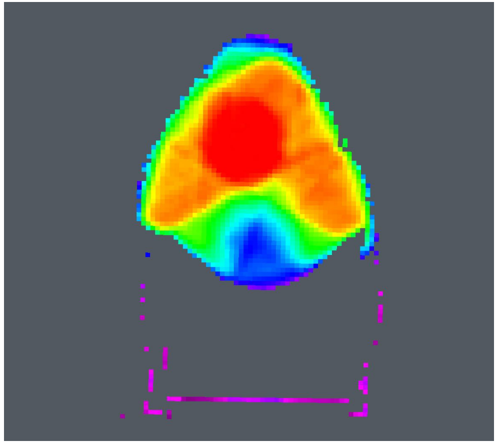
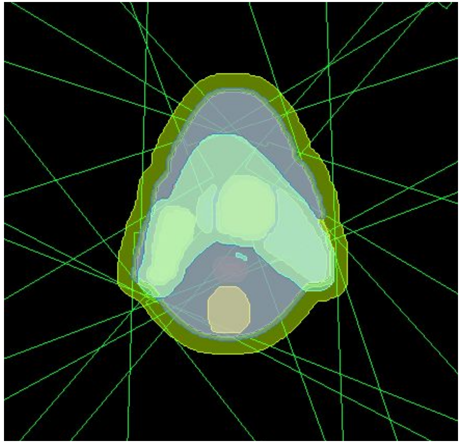
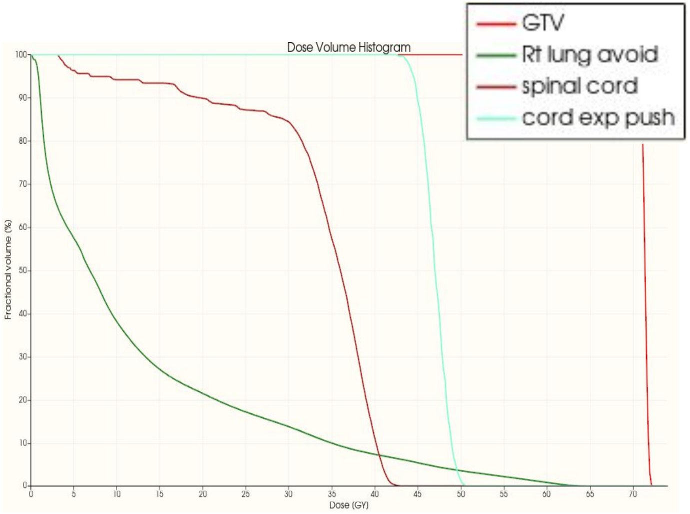
Treatment Planning System data flow

The patient: Dose Volume Histogram

single slice







In case the dose calculation resolution is relatively coarse, it's still possible to generate a high-resolution DVH through:

- Interpolation
- Resampling
- Subdivision
- Advanced Dose Calculation Algorithms

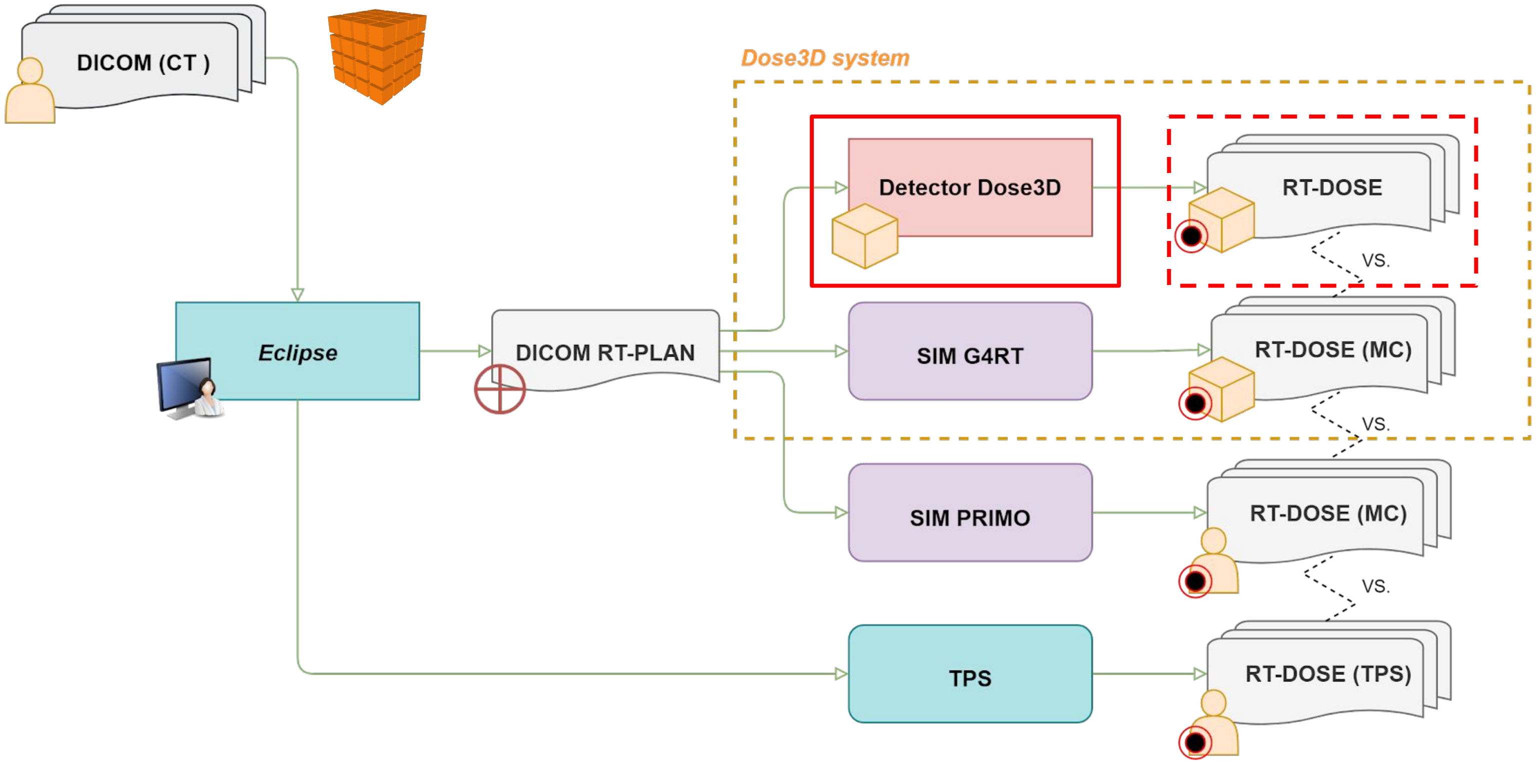
Dose delivered to the volume (GTV) that includes the tumor as seen on imaging studies wrt. other patient volumes

Imaging resolution matters

- Robust distinguishing between different types of tissues (e.g., bone, muscle, fat, and organs) and in identifying the boundaries between them.Consequently differentiation is essential for accurate diagnosis and treatment planning.

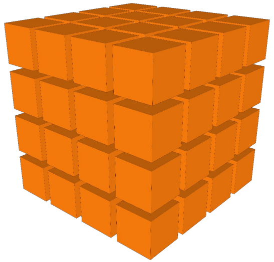
- The **spatial resolution of the dose** in patients is vital for delivering precise and effective treatment, optimizing patient safety, improving diagnostic image quality, enhancing treatment outcomes, and supporting ongoing research and development in medical imaging and radiation therapy.

Dose3D detector

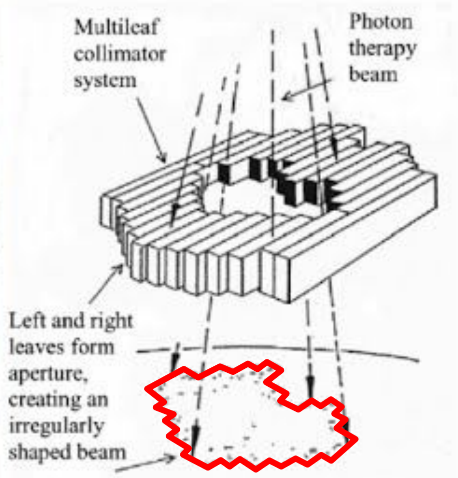


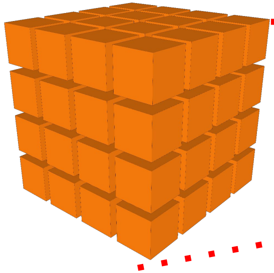
Dose3D detector

- Modular and dynamic detector/patient design
- Single cell of about 1 cc



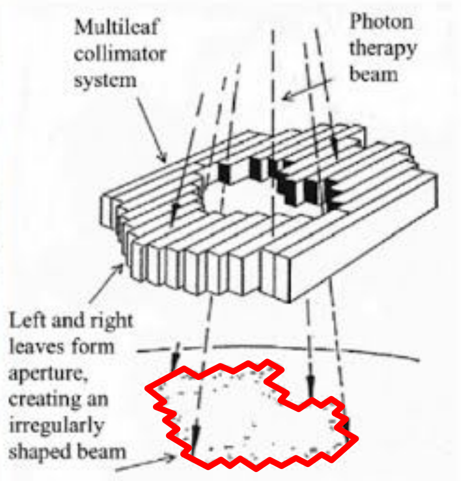
Dose3D measurement

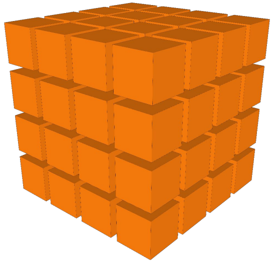




Detector prototype as a tower of cells within the printed enclosure

Dose3D MC simulation





Geant4-based app

- Handling geometric data from multiple sources in multiple formats
- Application should include the preparation of personalized patient treatment plans, hence specifically focusing on beam definitions as stored in the RT-Plan.
- Parameterized scoring (voxelized) cell

modified **U**-net

- U-net was first proposed by Ronneberger [1] and widely used in the field of semantic segmentation for biomedical purposes.

- The basic U-Net architecture consists of an encoder (contracting path) that captures context through downsampling and convolutions, and a decoder (expanding path) that upsamples and refines features.

- By combination of achievements [1][2] the **modified U-net** [3] works with SR where the expanding path (decoder) upsamples the feature maps to the desired high resolution, combining them with corresponding features from the encoder to preserve details.

[1] Ronneberger, O., Fischer, P., Brox, T. (**2015**). **U-Net: Convolutional Networks for Biomedical Image Segmentation**, https://doi.org/10.1007/978-3-319-24574-4_28
[2] Dong, C., Loy, C.C., He, K., Tang, X (**2014**). ***Learning a Deep Convolutional Network for Image Super-Resolution***, https://doi.org/10.1007/978-3-319-10593-2_13
[3] Lu, Z., Chen, Y. (**2019**). **Single Image Super Resolution based on a Modified U-net with Mixed Gradient Loss**, https://doi.org/10.48550/arXiv.1911.09428

Super-resolution

- Super-resolution (SR) techniques are frequently employed in the up-scaling process to enhance low-resolution images by adding details not present in the original.
- These techniques are typically applied to <u>2D images</u>, and their application to <u>3D images</u> remains less common, but…

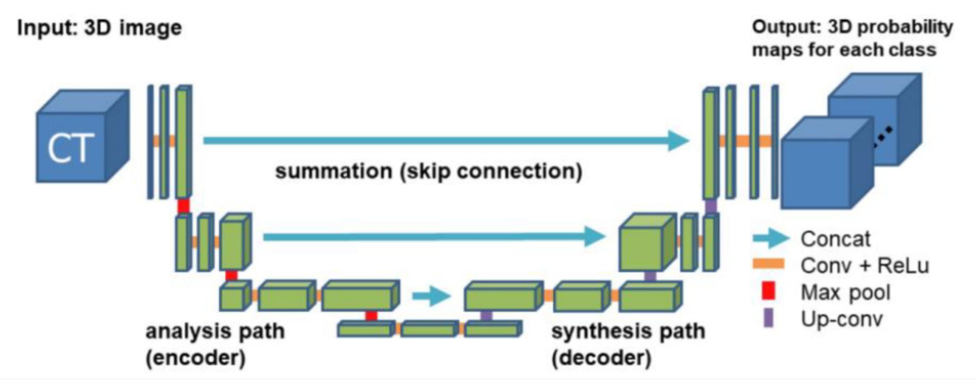
Original size 5472 x 3648

Neural network Upscaling Tool

https://app.ssw.imaging-saas.canon/app/images/nnut/sample2.png

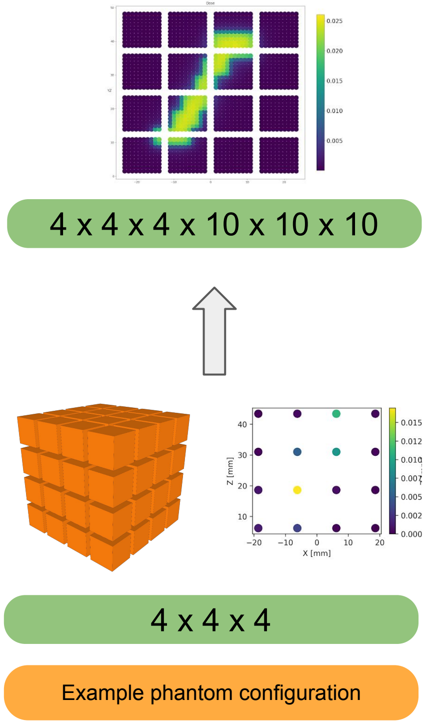
3D **U**-net

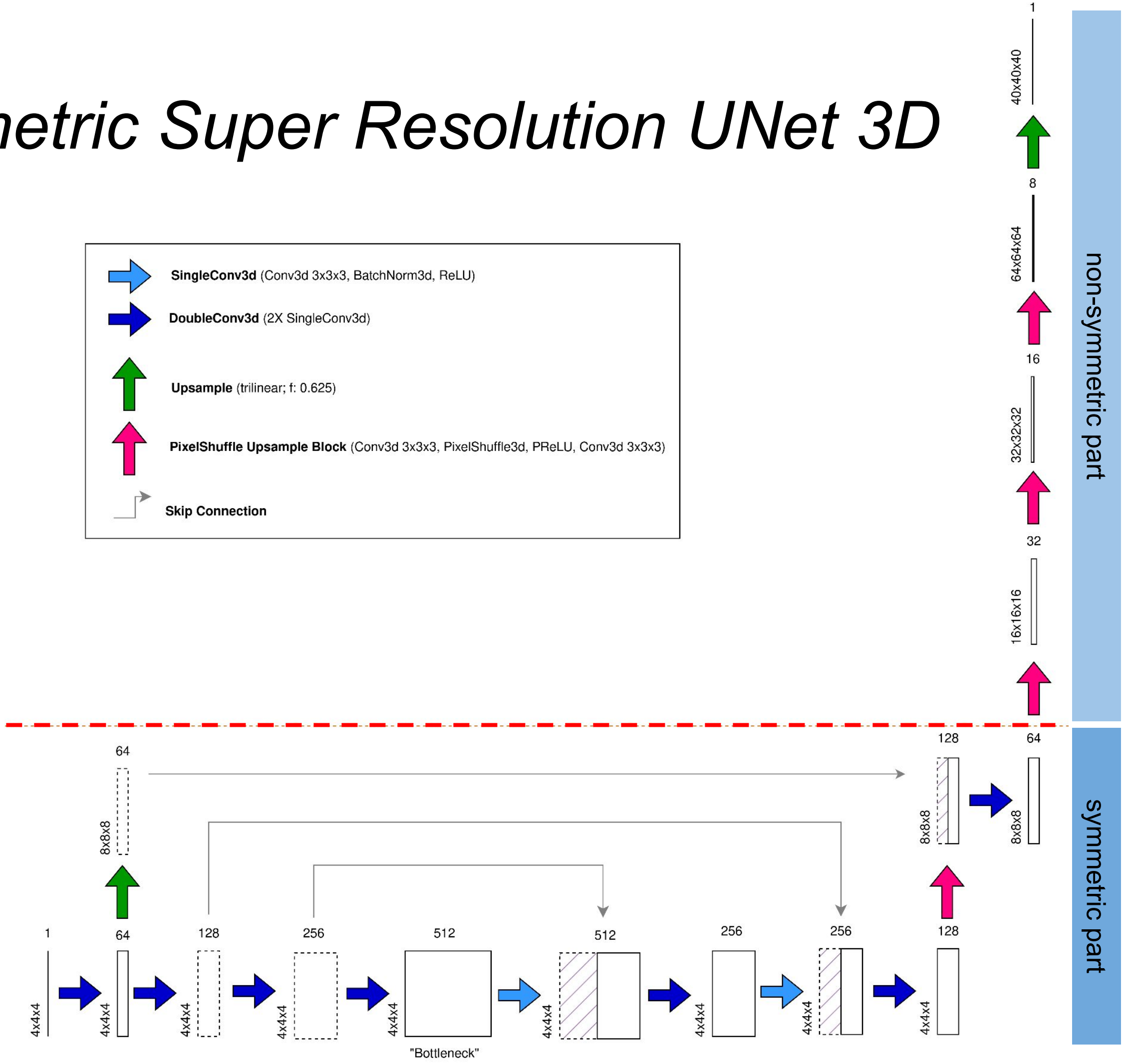
- By design, 3D U-net is a symmetric network (the model can be trained and inferred with different image sizes) and a typical encoder-decoder structure where the **encoder** structure analyses the input image and performs dimensionality reduction. The **decoder** path performs up-convolution to produce full image segmentation.



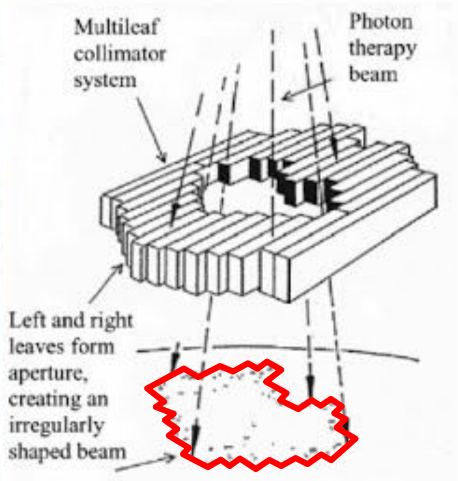
[4] Ö. Çiçek, A. Abdulkadir, S.S. Lienkamp, T. Brox, O. Ronneberger, (**2016**), **3D U-Net: Learning Dense Volumetric Segmentation from Sparse Annotation**, https://doi.org/10.48550/arXiv.1606.06650

non-Symmetric Super Resolution UNet 3D

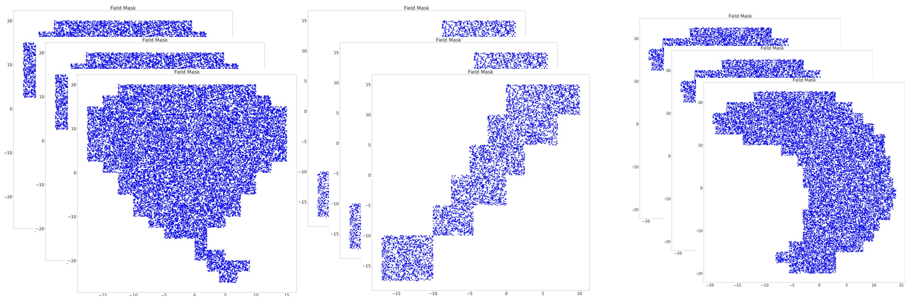




Training data



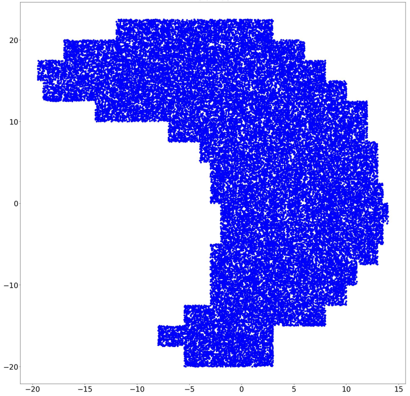
- The shape of the mask (stored in RT-Plan) significantly impacts the dose distribution in the phantom.



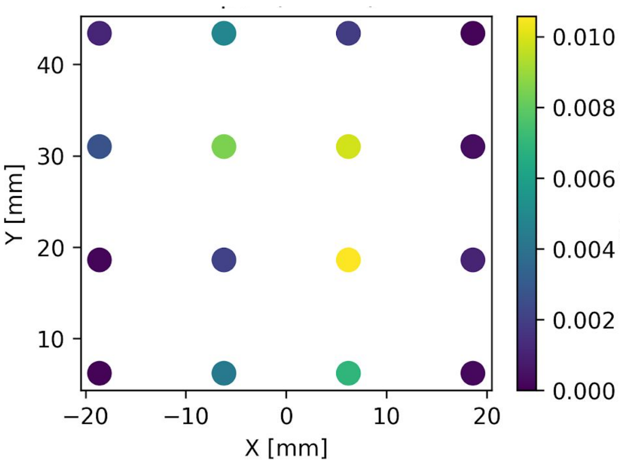
- Geant4 Monte Carlo simulation is used for enhancing resolution for the up-scaled training target images at the level of CT image
- Hand crafted feature: **field mask is parametrized and embedded** in the spatial dose distribution scored in the phantom volume
- Single model is being trained for 1 beam angle but different field mask
- Number of field mask simulated and datased augmented with horizontal/vertical mirroring and rotations

Training data

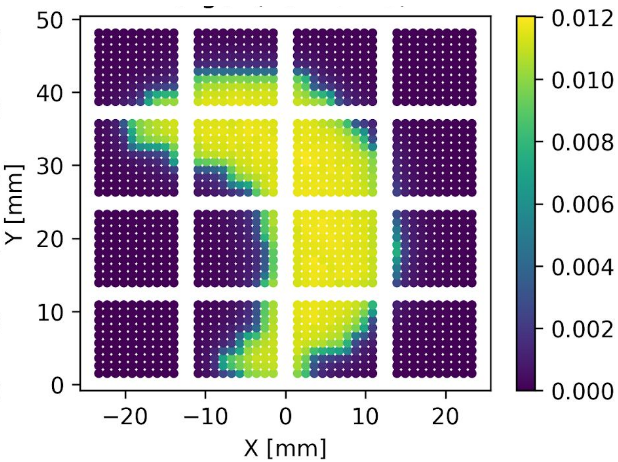
Field mask
(RT-Plan control point)



input: Dose for 4 x 4 x4
(single slice)

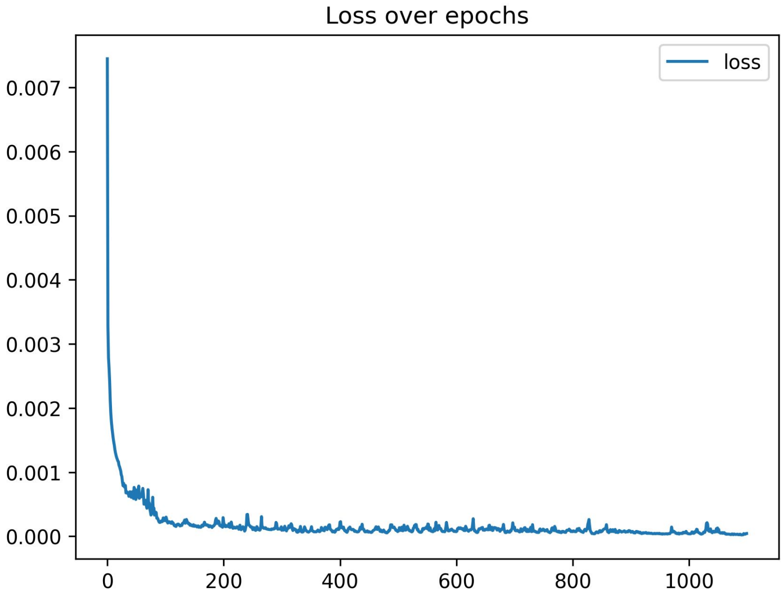


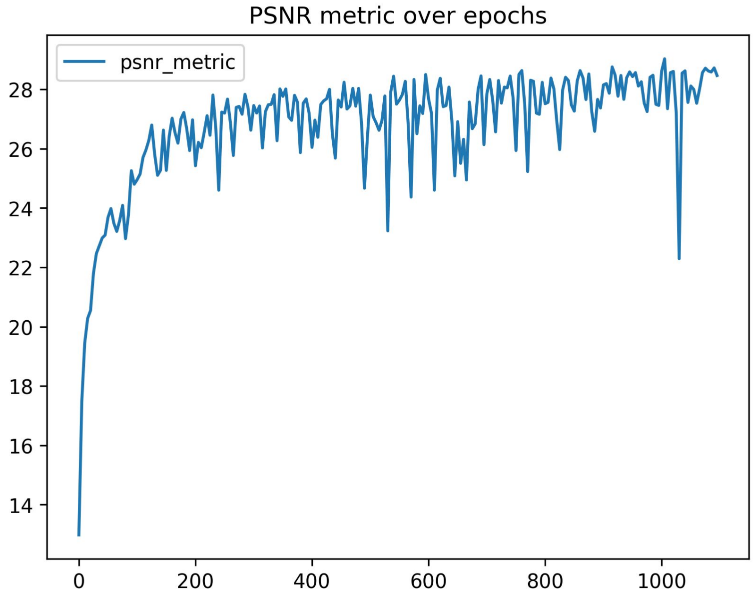
target: Dose for 4 x 4 x 4
x 10 x 10 x10 (single slice)



Training dataset: 264 input / target pairs
Validation dataset: 3 input / target pairs

Training stage





Loss function:
Mean **S**quared **E**rror

Model evaluation:
Peak **S**ignal to **N**oise **R**atio

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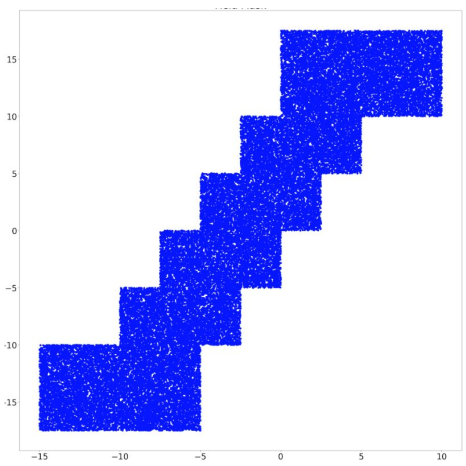
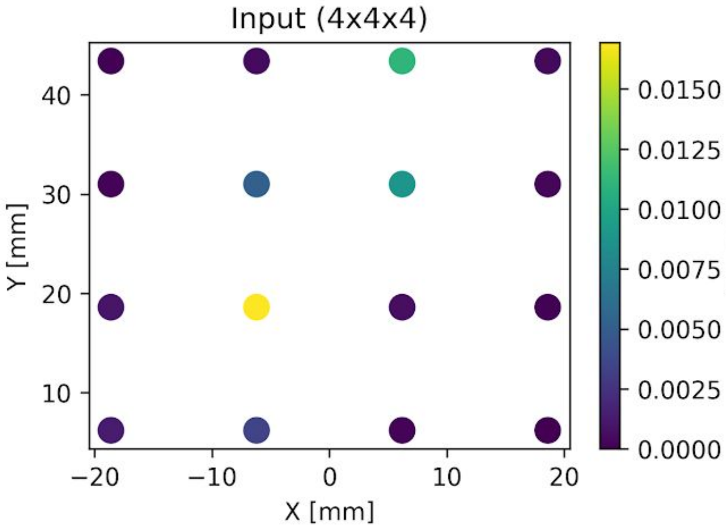
Model inference

Field mask
(RT-Plan control point)

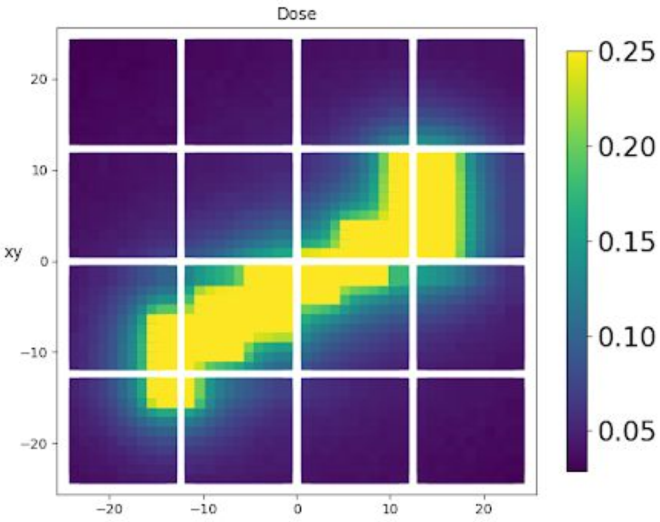


Dose from 4 x 4 x4
(single slice)

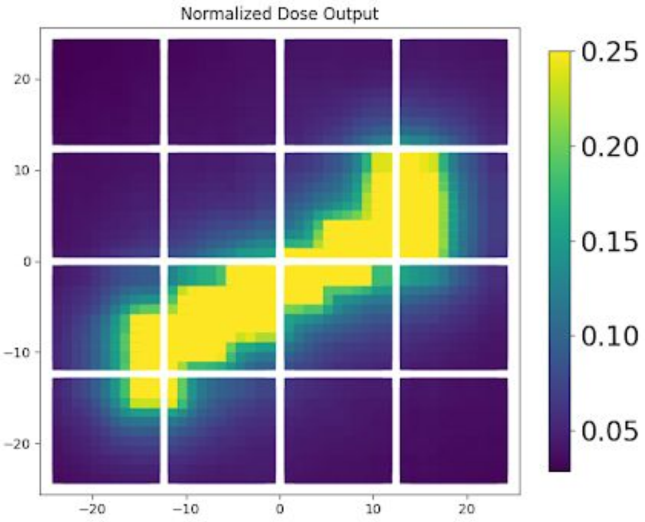


Model inference

Model output for 4 x 4 x 4 x 10 x 10 x10 (single slice)



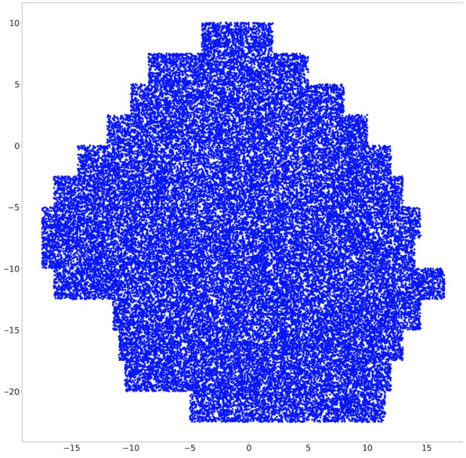
MC simulation for 4 x 4 x 4 x 10 x 10 x10 (single slice)



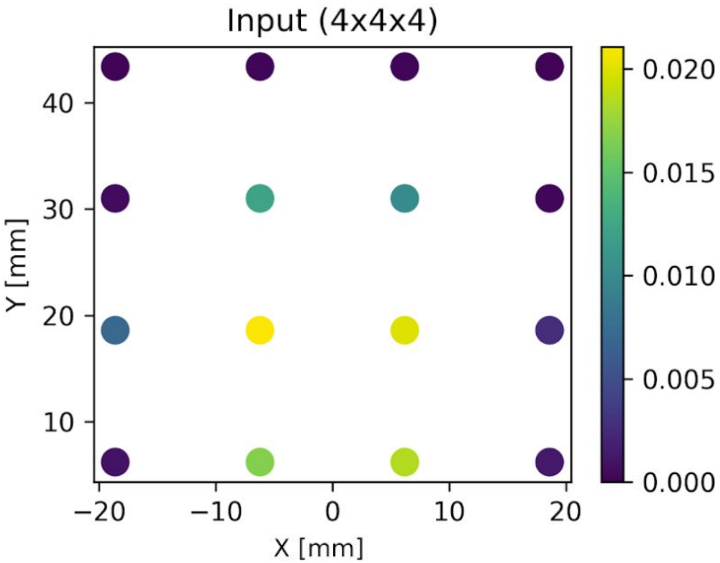
Gamma **I**ndex **P**assing **R**ate
2.5%/2.5 mm: **87.73 %**
5.0%/5.0 mm: **93.34 %**

Model inference

Field mask
(RT-Plan control point)

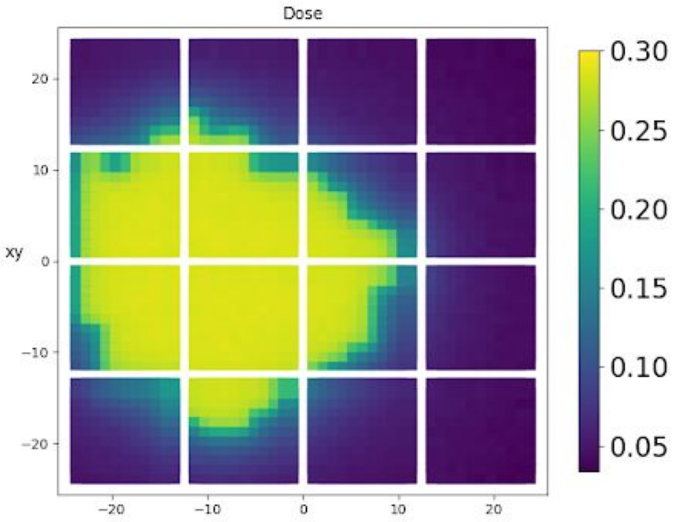


Dose from 4 x 4 x4
(single slice)

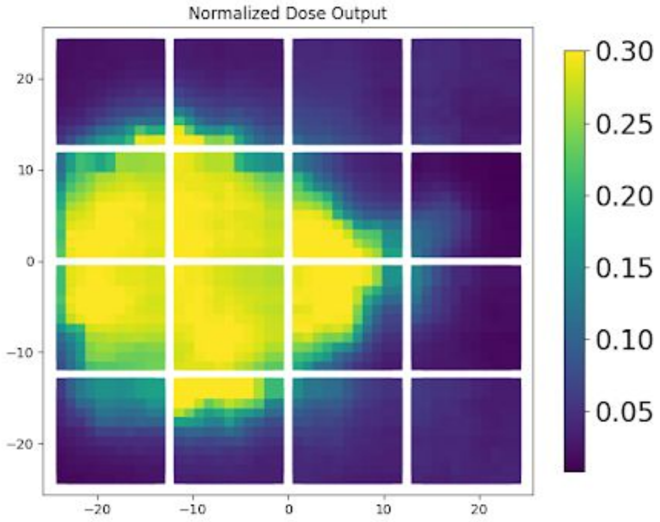


Model inference

Model output for 4 x 4 x 4 x 10 x 10 x10 (single slice)



MC simulation for 4 x 4 x 4 x 10 x 10 x10 (single slice)



Gamma **I**ndex **P**assing **R**ate
2.5%/2.5 mm: **69.51 %**
5.0%/5.0 mm: **89.64 %**

Summary

- Dose3D detector system has been designed and currently is being used in the test-beam campaigns.
- MC simulation platform is being developed as a digital twin of Dose3D
- ML-based algorithms are being developed for upscaling the future measurement data to the level of the CT resolution
- A standard gamma analysis of 2.5%/2.5 mm and 5%/5 mm was performed on the spatial dose distribution predicted by the nSSRUnet3D network and the simulated sample in the test dataset, demonstrating promising gamma pass rates.
- Our preliminary results underscore the significant potential of DL methods in upscaling the dose delivered to Dose3D-like phantom for the radiotherapy treatments.

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Akademia Górniczo-Hutnicza
im. Stanisława Staszica w Krakowie
AGH University of Krakow

Narodowy Instytut Onkologii
im. Marii Skłodowskiej-Curie
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Thank you.

Dose3D-Future Collaboration

AGH University of Krakow

Faculty of Physics and Applied Computer Science

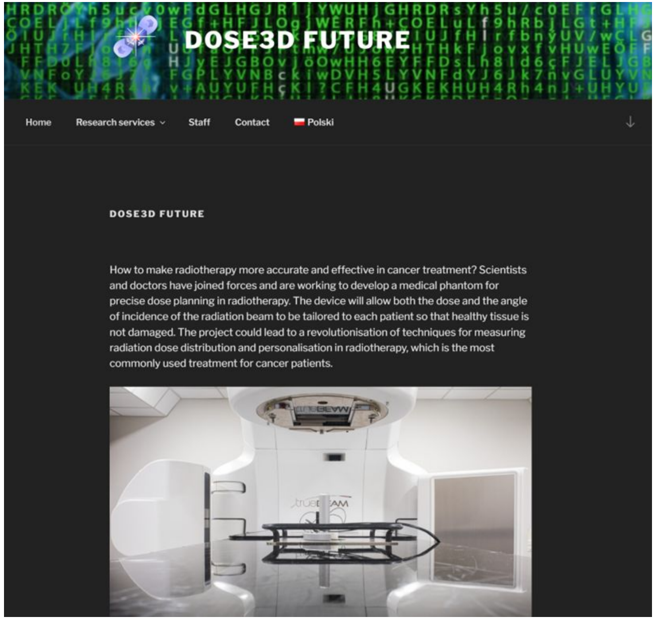
Department of Interactions and Detection Techniques (KOiDC) AGH

Maria Sklodowska-Curie National Research Institute of Oncology Krakow Branch

Foundation for Polish Science

Continuation of grant no.:

POIR.04.04.00-00-15E5/18



https://dose3d-future.fis.agh.edu.pl/

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BACKUP SLIDES

Performance evaluation

Gamma index Passing Rate (**GPS**)

- How well the delivered dose matches the planned dose by comparing corresponding points in the two distributions,
- In this case: model inference vs simulation for spatial dose distribution

$$\Gamma(\mathbf{r}_{\text{real}}, \mathbf{r}_{\text{pred}}) = \sqrt{\frac{\Delta \mathbf{r}^2(\mathbf{r}_{\text{real}}, \mathbf{r}_{\text{pred}})}{\delta r^2} + \frac{\Delta D^2(\mathbf{r}_{\text{real}}, \mathbf{r}_{\text{pred}})}{\delta D^2}}$$

- Analysis criteria: **X% / Y mm**:
  - **X %** represents the percentage dose difference allowed between the calculated and measured doses at corresponding points.
  - **Y mm** indicates the maximum distance-to-agreement (DTA) allowed between the calculated and measured positions,
- GPS of **95%** or higher is often considered acceptable with a **3%/2** mm distance-to-agreement (DTA) criterion