Faster than light: GPU and DL dose calculations for keV photons (INTRABEAM)

Grupo de Física Nuclear UCM

Paula Ibáñez García

Grupo de Física Nuclear & IPARCOS

Universidad Complutense de Madrid

Intraoperative radiation therapy (IORT)

Technique that involves precise delivery of a large dose of ionizing radiation to the tumor or tumor bed during the surgery.

Beddar *et al.* 2006. Med. Phys. **33** 1476-89

Advantages:

- Reduction of secondary tumors.
- Better definition of the treatment area.
- Maximization of the radiobiological effect with a high and localized dose.
- Less secondary effects than in conventional radiotherapy.

Wenz *et al.* 2020. Rad. Oncol. **5** 11

INTRABEAM device

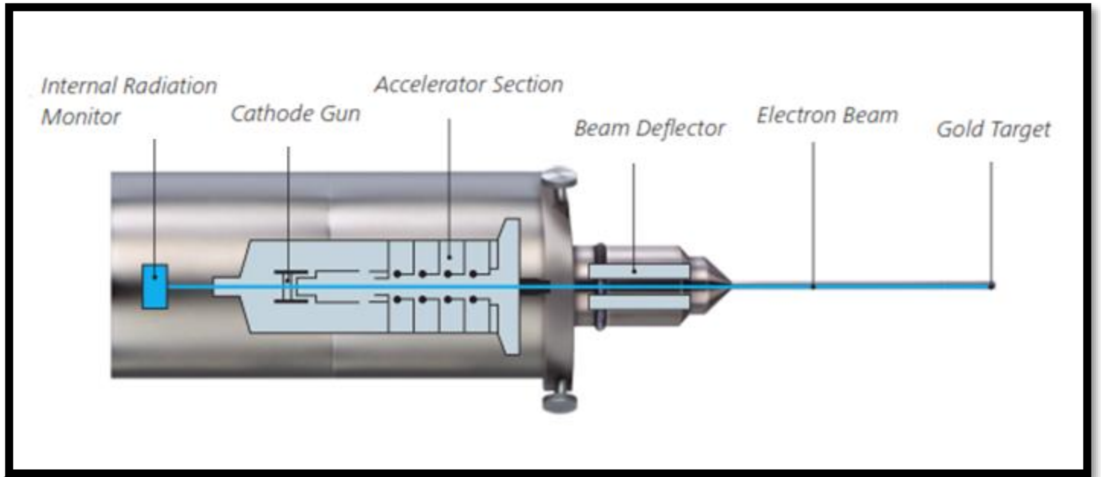
Low-energy X-rays Intraoperative Radiotherapy (XIORT)

Miniature X-ray source

- 50 kV electron beam hitting a gold target
- Low-energy X-rays (Up to 50 keV)

Applicators attached to the source

-Most common: Spherical applicator



Intrabeam (Carl Zeiss Meditec)

Treatment Plan System (TPS) for INTRABEAM

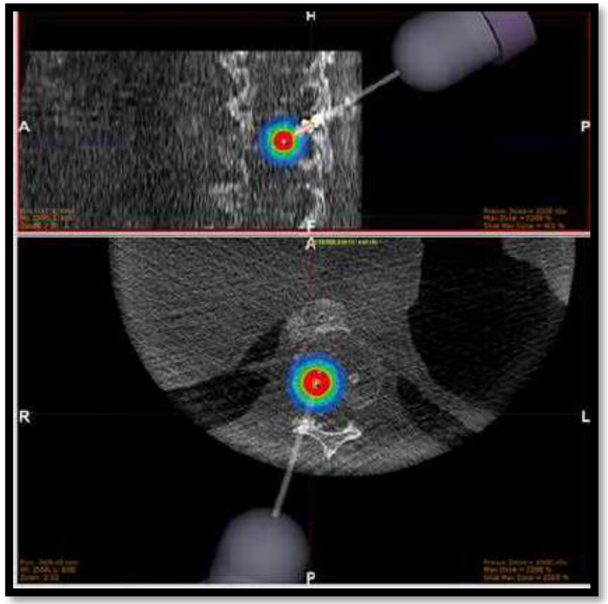
Decission of the treatment *in situ*

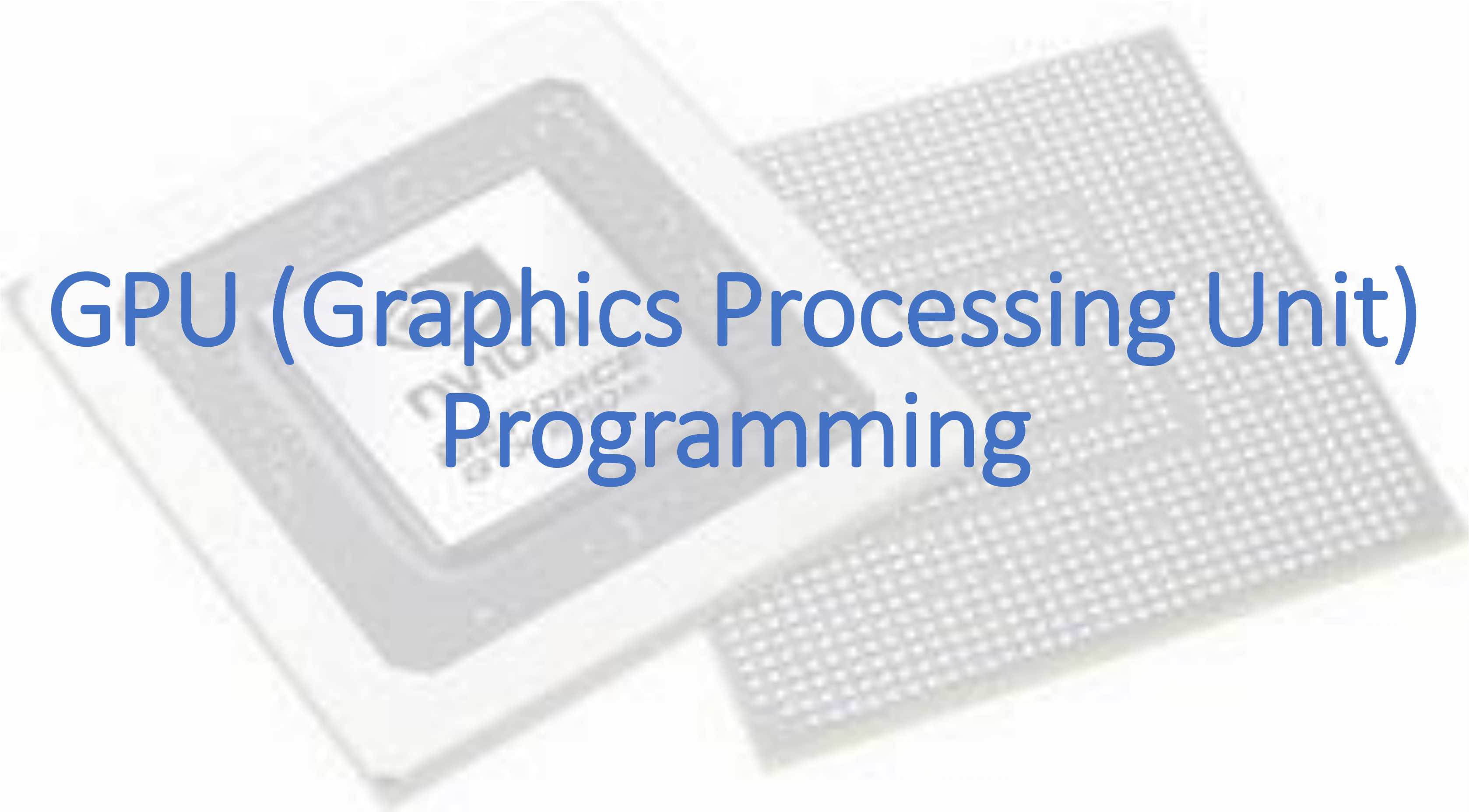
Monte Carlo simulations
- Low efficiency
- High number of particles

Long simulations

Code accelerations
- GPU-based implementations
- DL approaches

Radiance





GPU (Graphics Processing Unit) Programming

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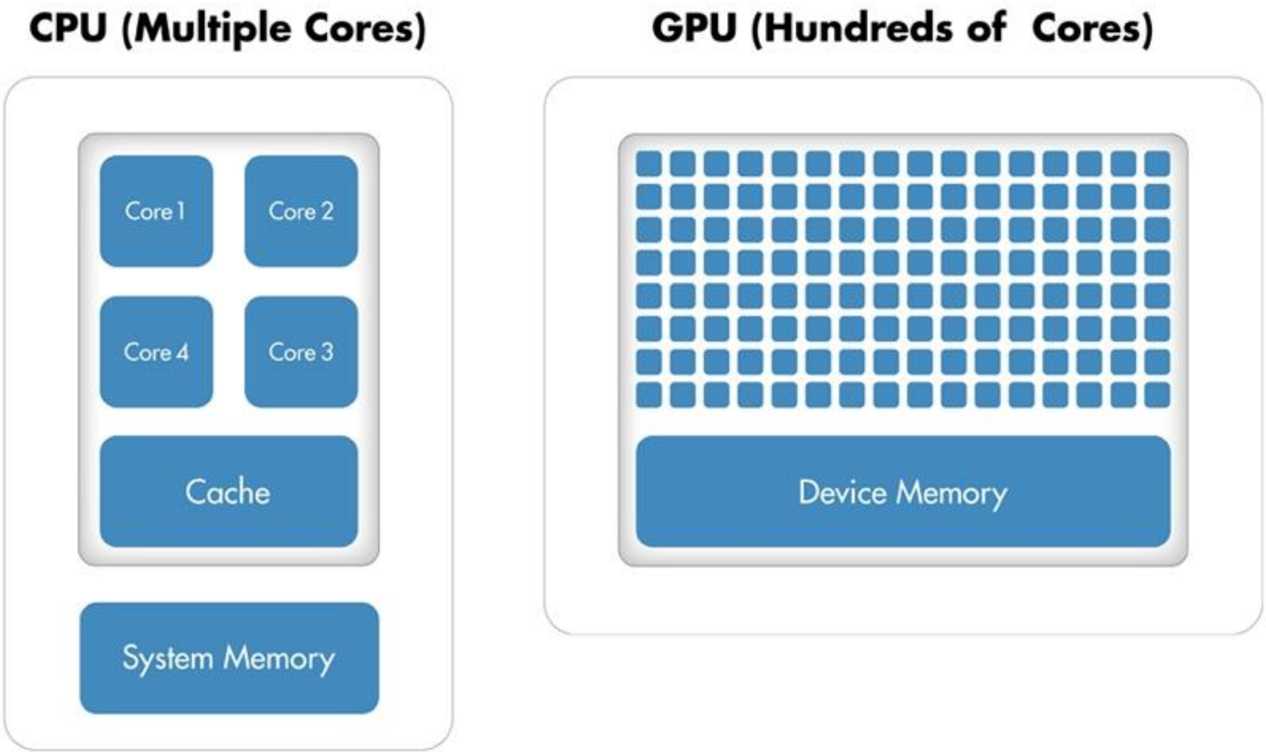
Massive parallelization



"A CPU consists of a few cores optimized for sequential serial processing while a GPU has a massively parallel architecture consisting of thousands of smaller, more efficient cores designed for handling multiple tasks simultaneously."

Nvidia webpage

GPU- based dose computation algorithms

Two dose computation algorithms

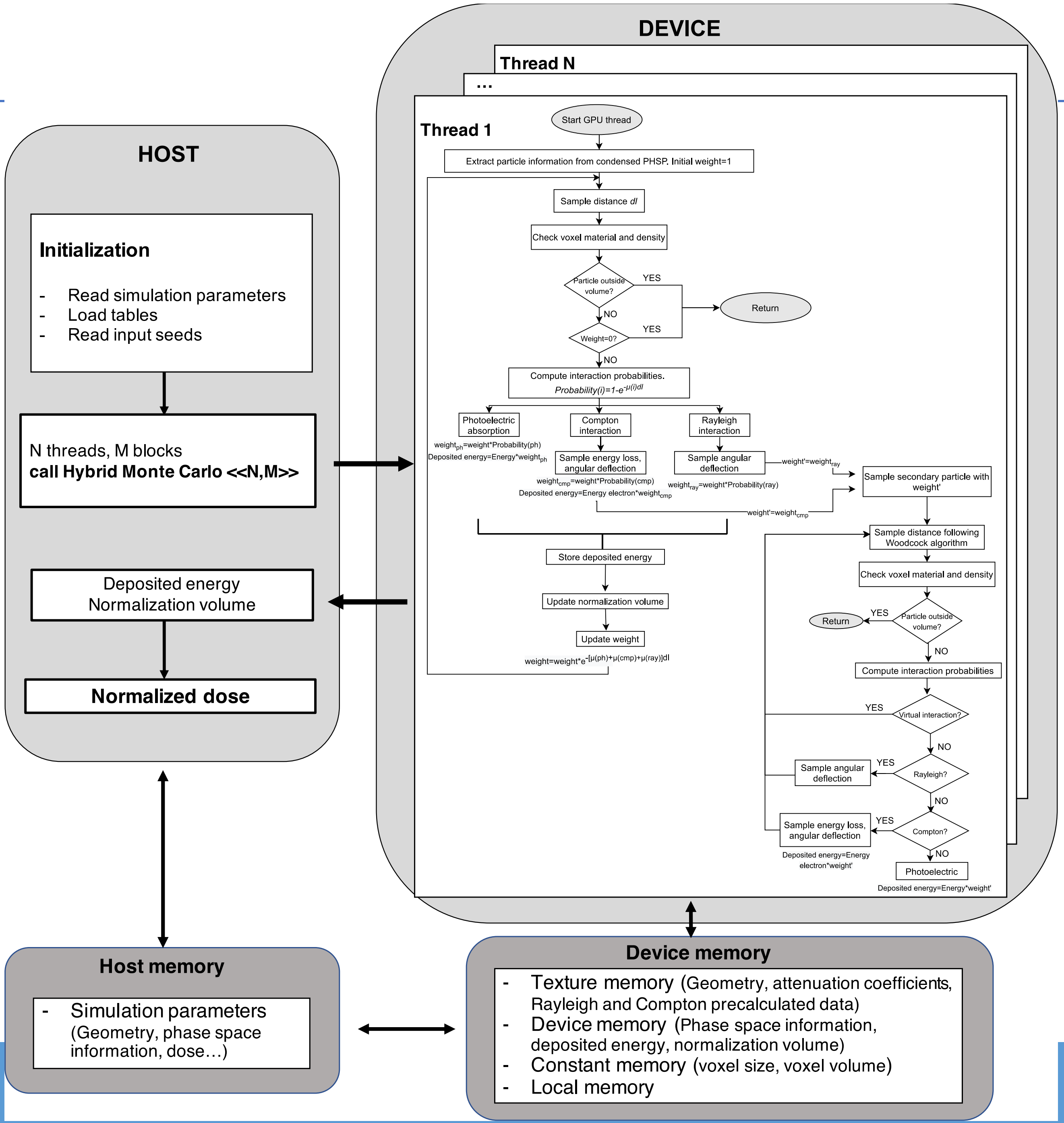
GPU-MC

GPU-HMC

- Use of meta-histories.
- Interaction forcing and condensed interactions.
- Dose normalization.

- Common ingredients in both calculations
  - Photoelectric, Rayleigh and Compton effects for photons up to 1 MeV.
  - Attenuation coefficients extracted from PENELOPE database.
  - Local electron absorption: variance reduction
  - Woodcock tracking algorithm: very efficient on GPU

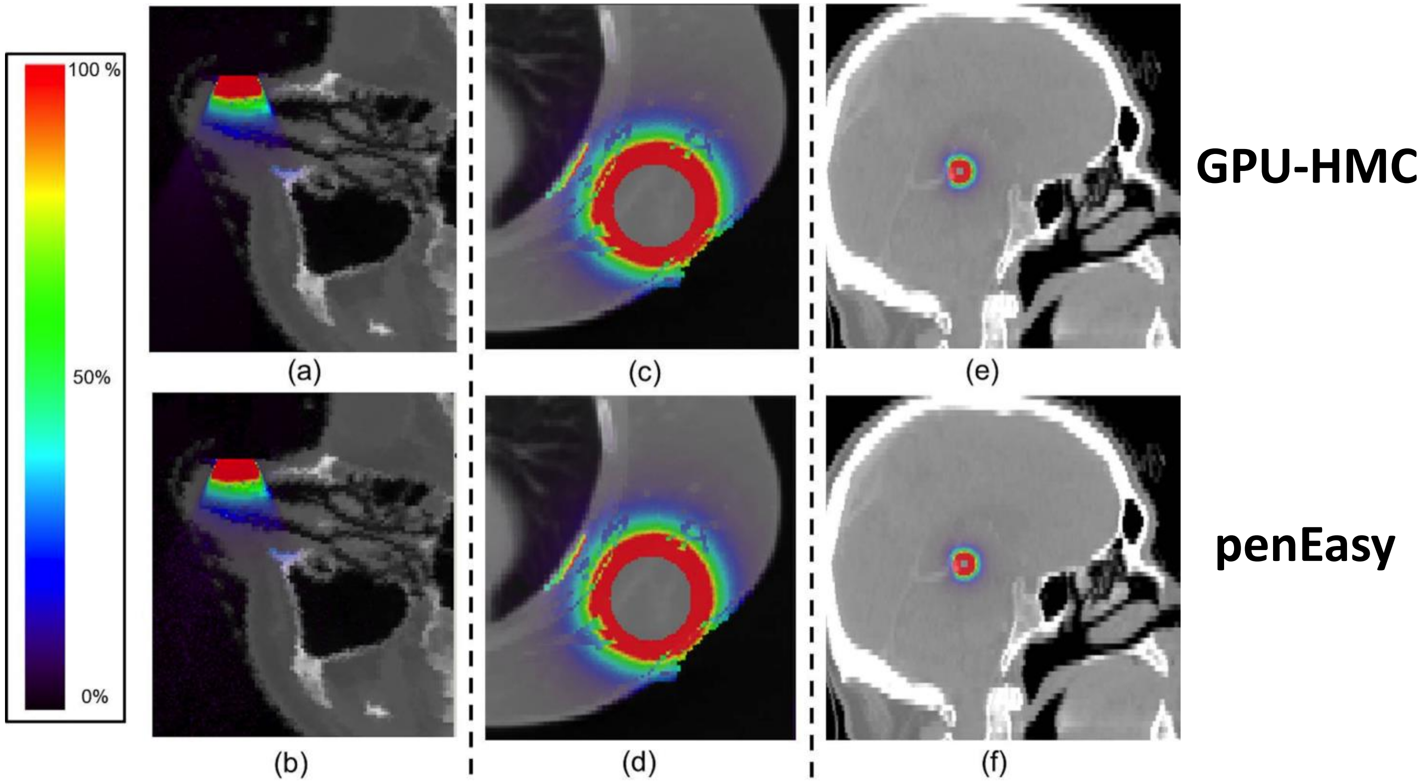
P. Ibáñez *et al.* 2021. Med Phys 48(12), 8089-8106.



Grupo de Física Nuclear

GPU- based dose computation algorithms

Some examples



Comparison with penEasy. Same level of statistical noise

Treatment type	Code	Simulation time (s)	Speed factor	7%-0.5 mm gamma
Sarcoma	GPU-MC	0.8	$3.8 \cdot 10^4$	99.9
	GPU-HMC	0.2	$1.7 \cdot 10^5$	99.1
Breast	GPU-MC	4.3	$2.1 \cdot 10^4$	99.6
	GPU-HMC	0.5	$1.6 \cdot 10^5$	99.4
Brain	GPU-MC	0.04	$2.0 \cdot 10^4$	99.2
	GPU-HMC	0.02	$4.3 \cdot 10^4$	99.0

GPU: NVIDIA GeForce RTX 3090
CPU: Intel Xeon W-2155

P. Ibáñez *et al.* 2021. Med Phys 48(12), 8089-8106.

GPU- based dose computation algorithms

In all cases:

- > 10.000 speed factor compared to penEasy
- > 99% gamma passing rate
- Simulation time with GPU-HMC in less than 1 s
- Simulation time with the GPU-MC in less than 5 s

Comparison with penEasy. Same level of statistical noise

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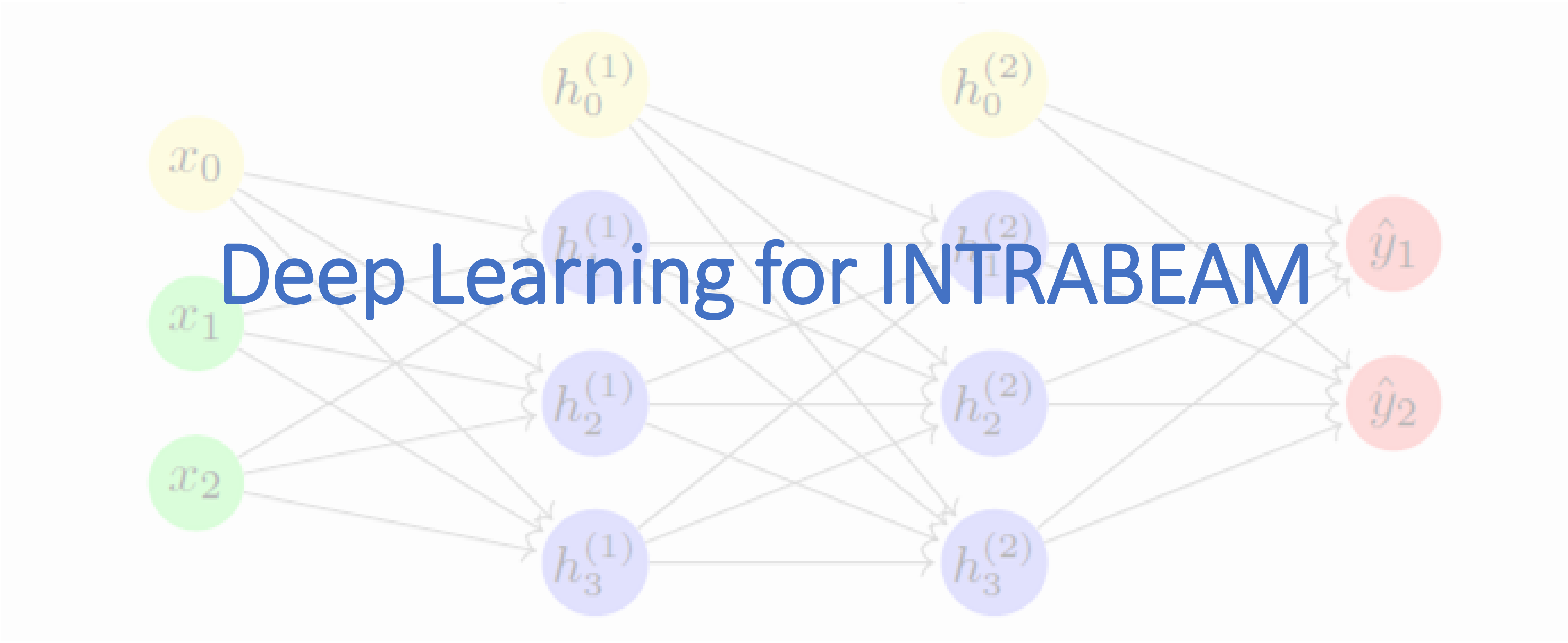
Deep Learning for INTRABEAM

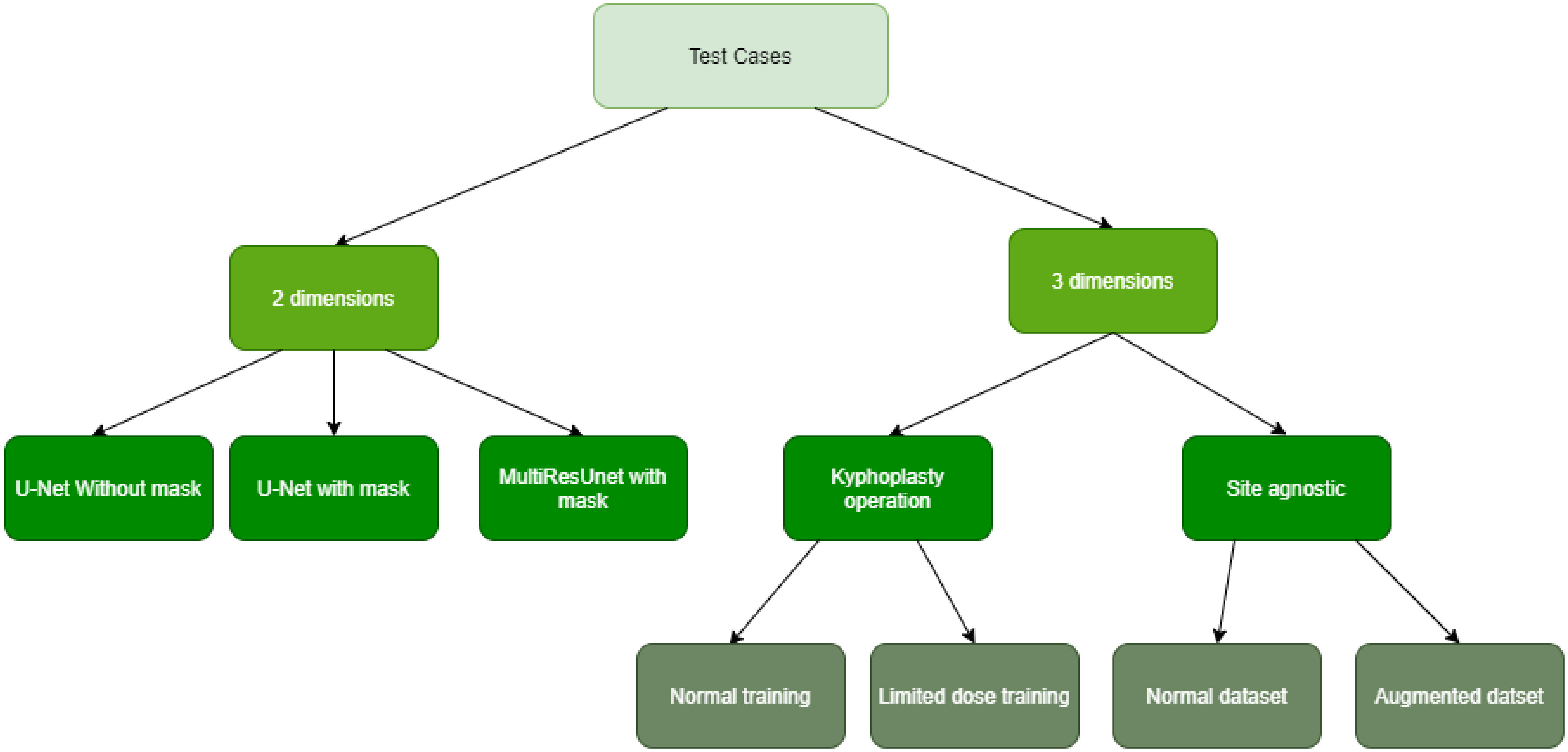


Objectives

- Train a deep learning model to predict the dose distribution in a sub-second time scale.
- Evaluate different neural networks to do the task.
- Examine the possibility of using data augmentation to improve the results of the neural network.

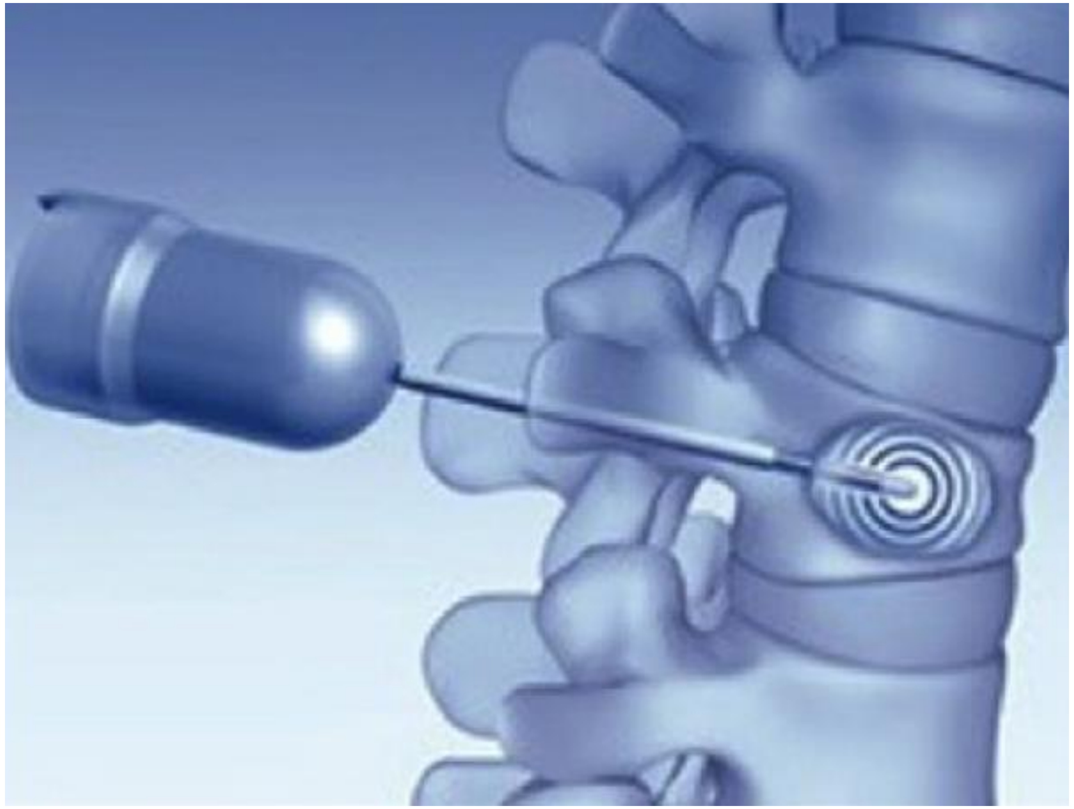
- **Databases from the HMC**
  - Fast
  - Accurate
  - No statistical noise

Deep Learning for INTRABEAM



3D dataset. Kyphoplasty operation dataset and training

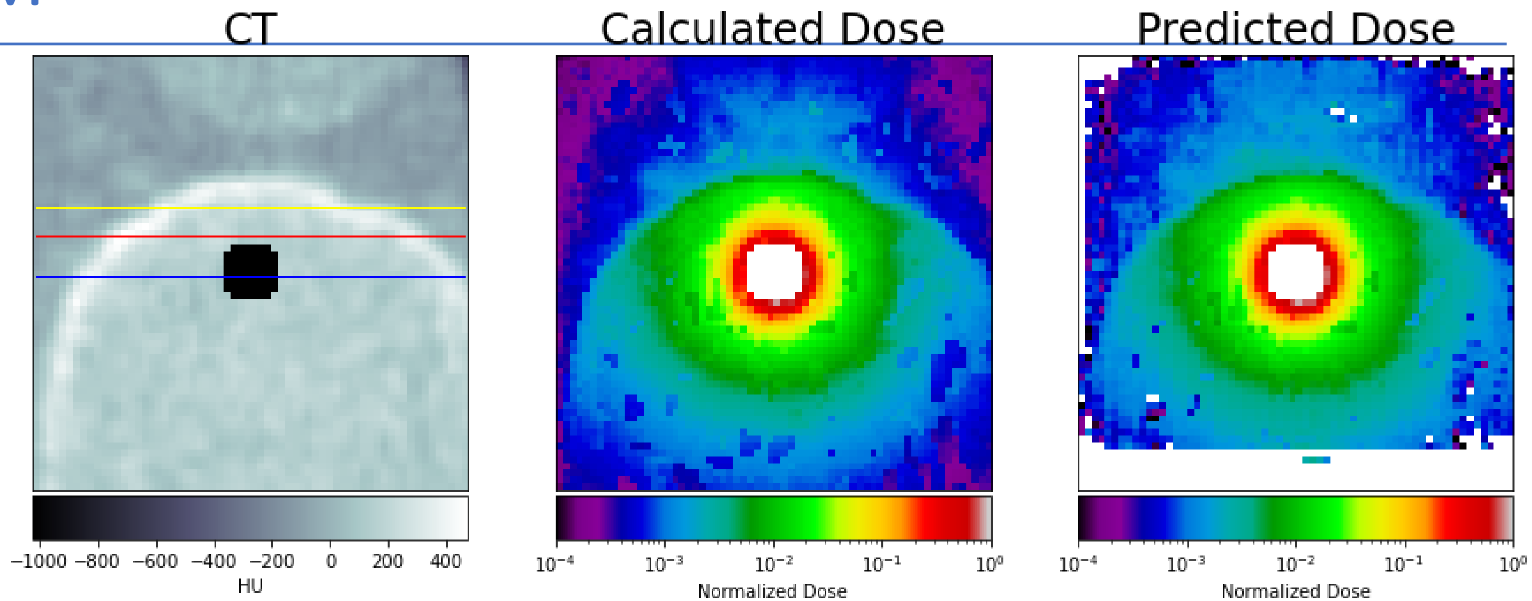
- The applicator used is the needle.
- The datasets used in training consisted of 48 images as a training set, 5 images as a validation set.
- The dataset was generated with the HMC.
- MultiResUnet with mask
- The image size was 64X64X64 with a voxel size of 0.5mmX0.5mmX0.5mm.
- The training took 2.5 hours.
- The number of epochs was 500.
- Batch size was 2.

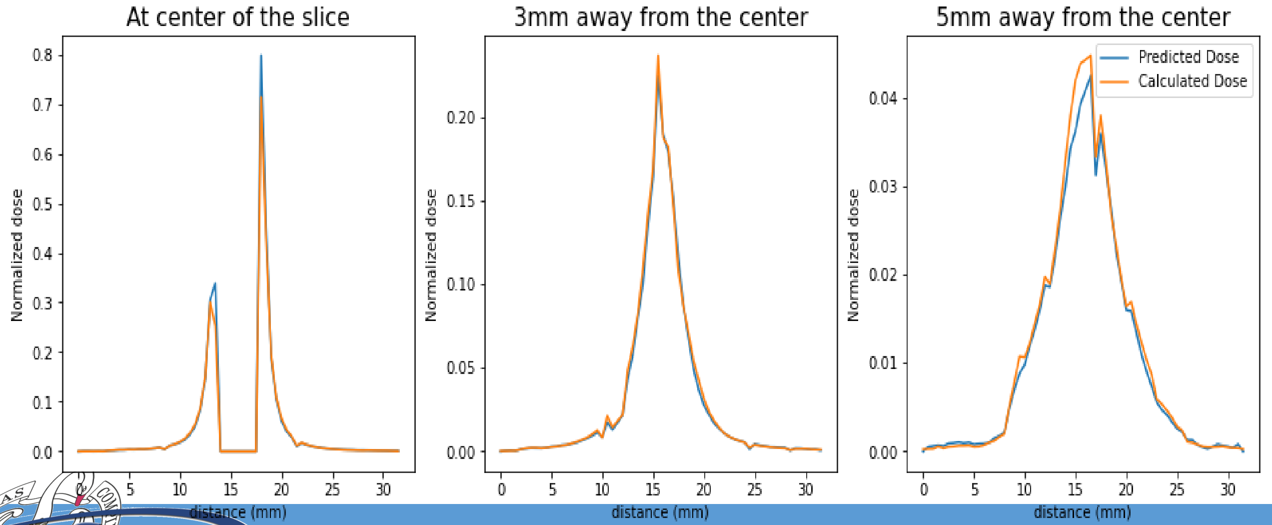


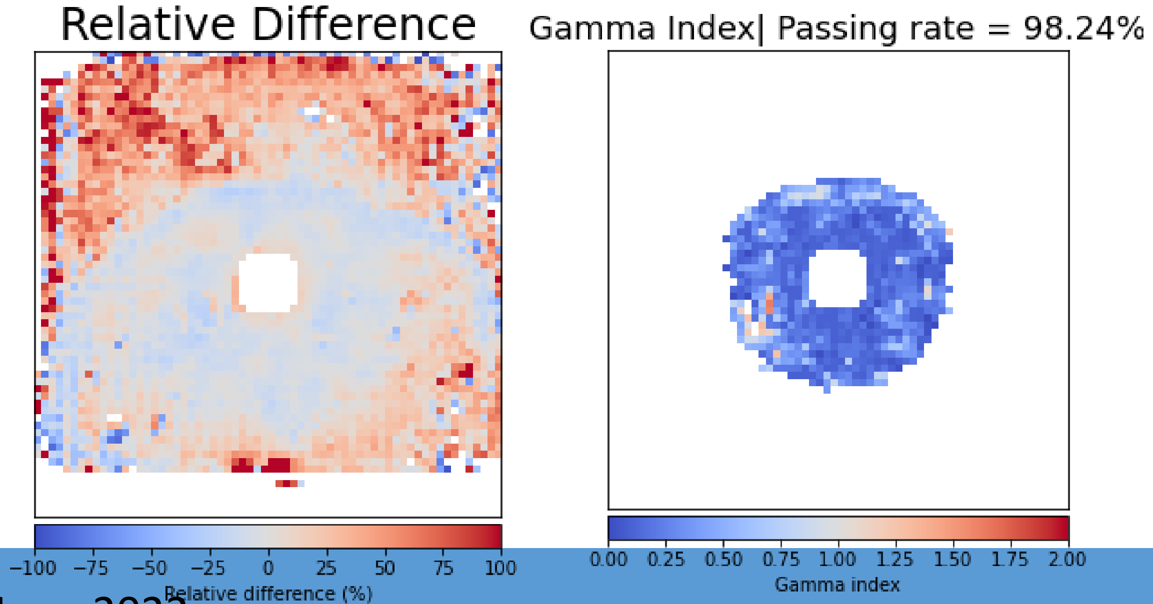
A. Sethi et al.2018. Front. Oncol., 26

Deep Learning for INTRABEAM

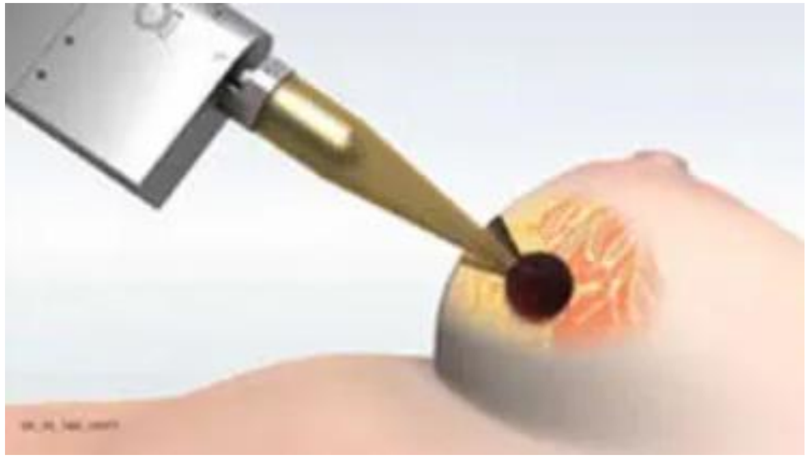
Results Needle applicator







3D site agnostic dataset and training with data augmentation

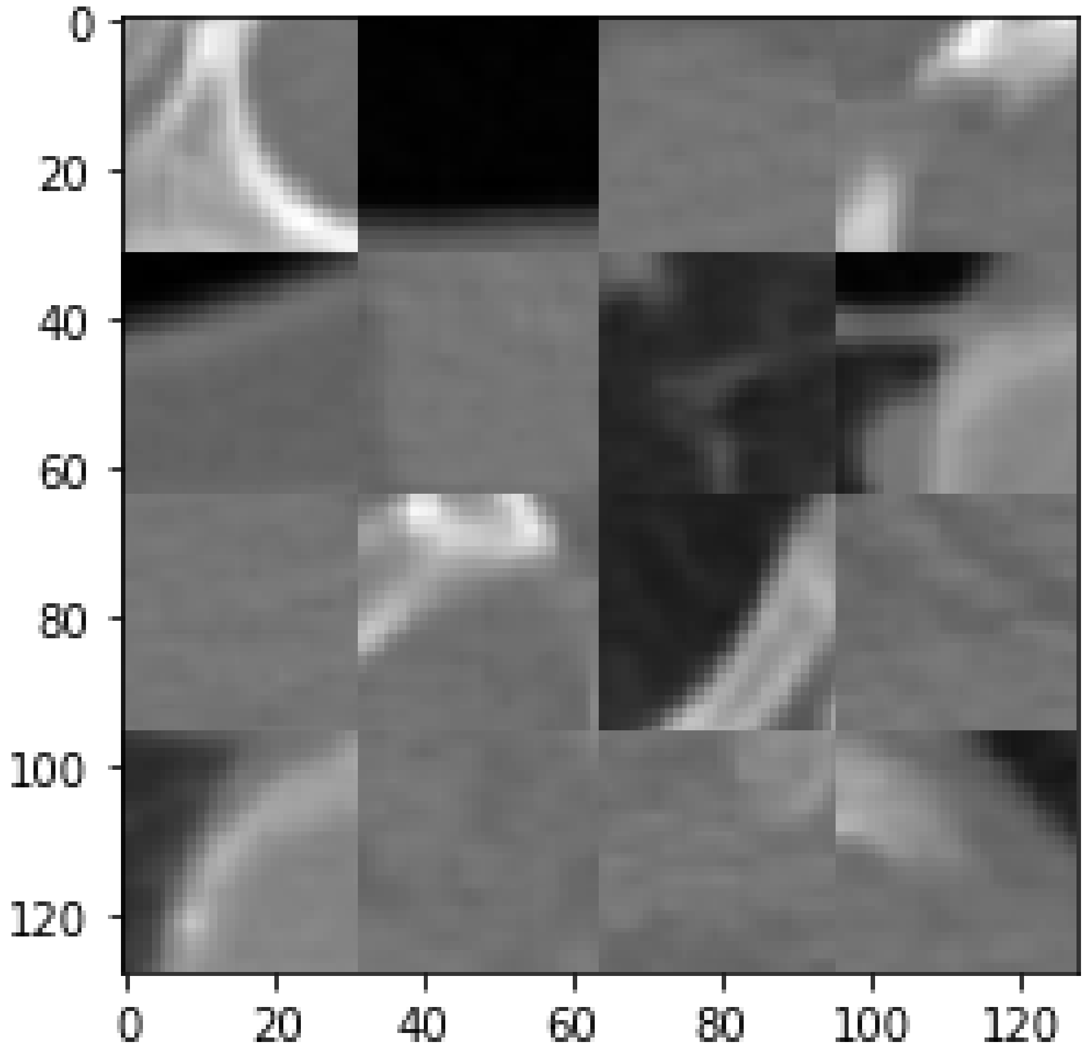


Intrabeam (Carl Zeiss Meditec)

- The applicator is spherical
- The datasets used in training consisted of 720 images as a training set and 80 images as a validation set.
- The dataset was calculated with the HMC.
- MultiResUnet with mask
- The image size was 128X128X64 with a voxel size of 0.5mmX0.5mmX0.5mm.
- The training took 24 hours.
- The number of epochs was 200.
- Batch size was 2.

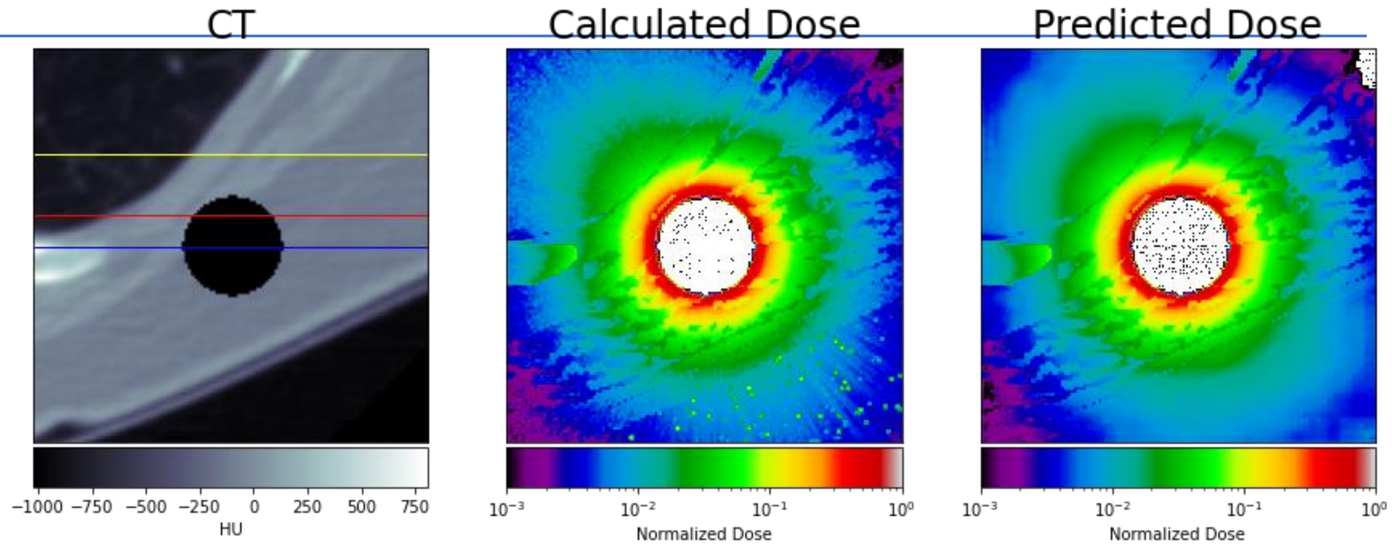
Data augmentation

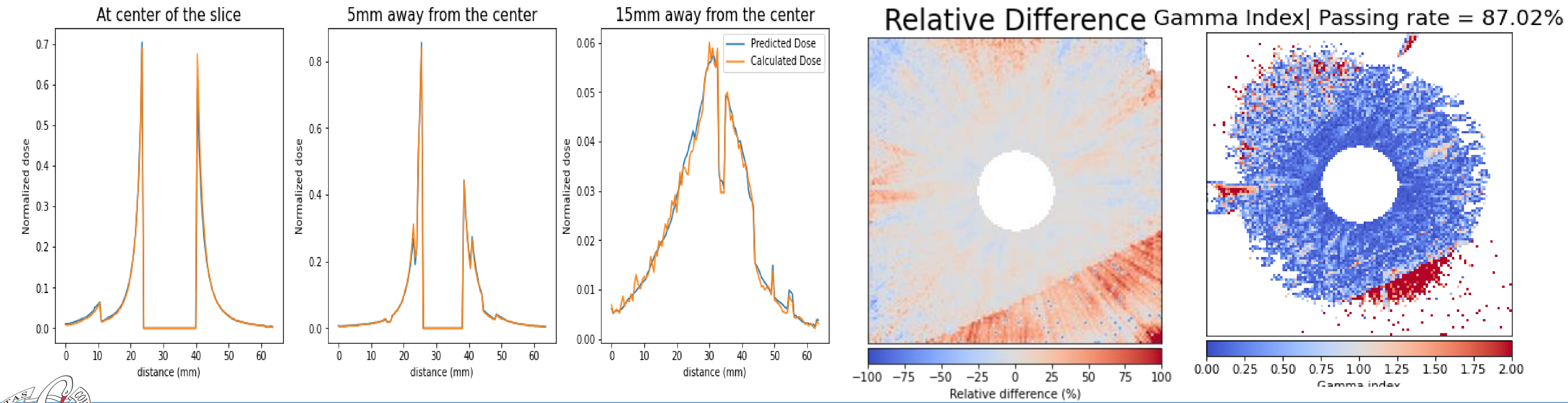
- Image augmentation techniques is proven to improve the results of deep learning.
- but conventional image augmentation is not feasible for our case.
- This image was split into 16 parts and each part was taken from a different image in the dataset.
- The dose is then calculated with the HMC code.



Deep Learning for INTRABEAM

Results Augmented dataset





Conclusions

- Accurate dose calculation for the INTRABEAM in real time is possible.
- Realistic dose distributions can be obtained with the GPU-HMC in less than 1 second for any INTRABEAM applicator.
- The ultra-fast GPU simulations allow the creation of realistic datasets free of statistical noise in a short time.
- Deep learning approaches can be used for the INTRABEAM 2D and 3D dose calculation.
- Other type of applicators will be tested with DL approaches as well.

Thank you for your attention

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Nuclear Physics Group
Universidad Complutense de Madrid

GPU- Hybrid MC

Meta-Histories

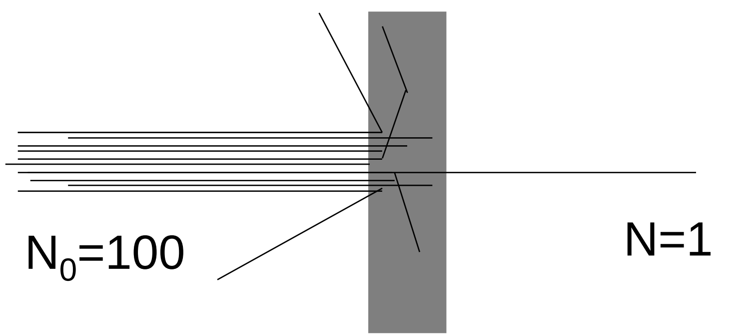
1 meta-history =N photons.

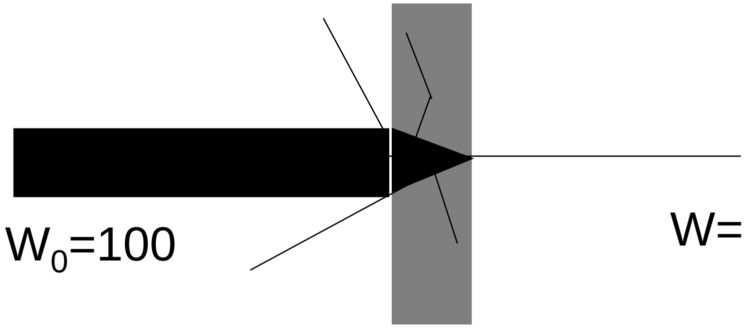
Read and extracted from a condensed PHSP.

After each interaction the weight of the meta-history is updated.

Dose calculated from the reduction of the weight of each meta-history.

Constant number of meta-histories along the volume.





Interaction forced and condensed interactions

After every step the meta-history is forced to interact.

Effect of the interaction on the weight of the meta-history.

Secondary particles

If $\text{Prob}_{\text{compton or Rayleigh}} > \text{Threshold}$.

N secondary particles with weight ω/N.

Woodcock tracking algorithm

Electrons locally absorbed

Dose Normalization

If too few meta-histories: Dose patterns due to subsampling.

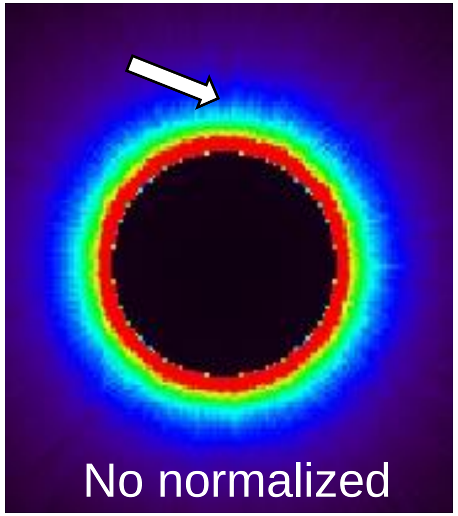
Meta-histories never die →*A priori* knowledge of the number of meta-histories and interactions in each voxel.

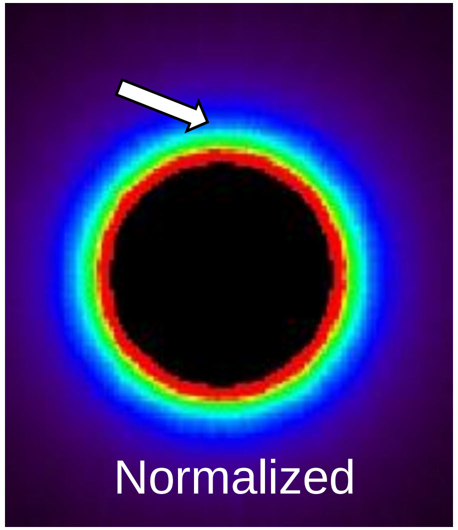
Fluency: Source geometry

(Weight: Phantom materials)

Normalization: Correction by the estimated number of interactions in each voxel.

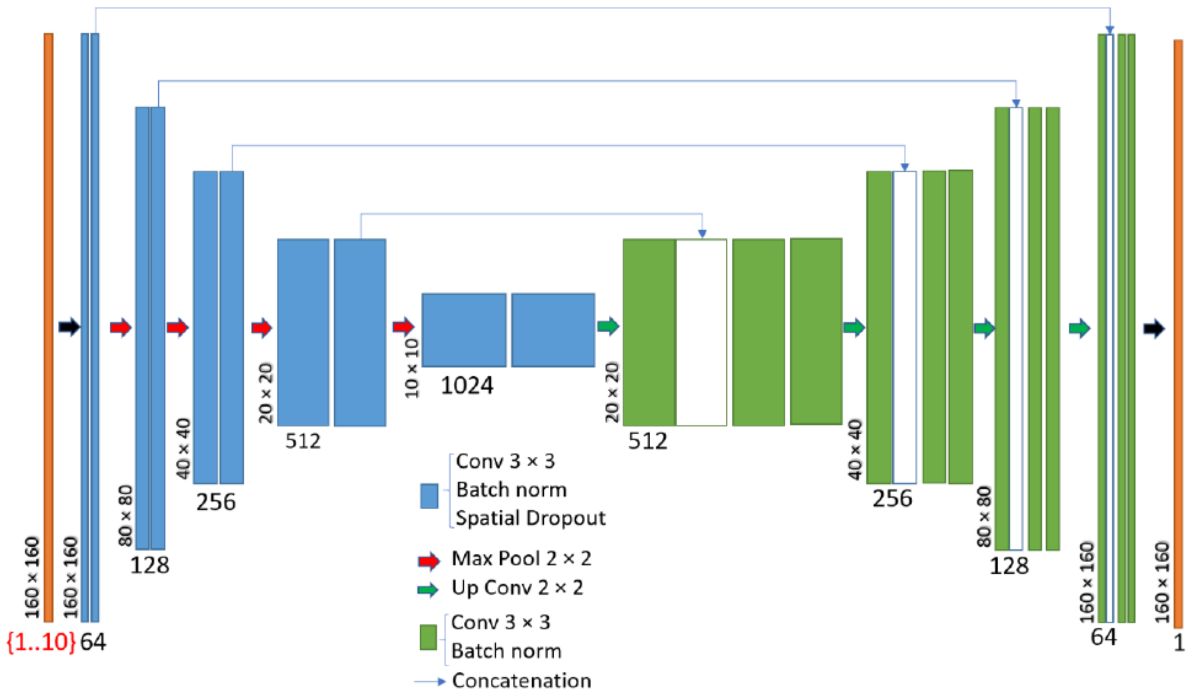
$$norm\_dose(x,y,z) = \frac{dose(x,y,z)}{norm(x,y,z)}\, fluency(x,y,z)$$





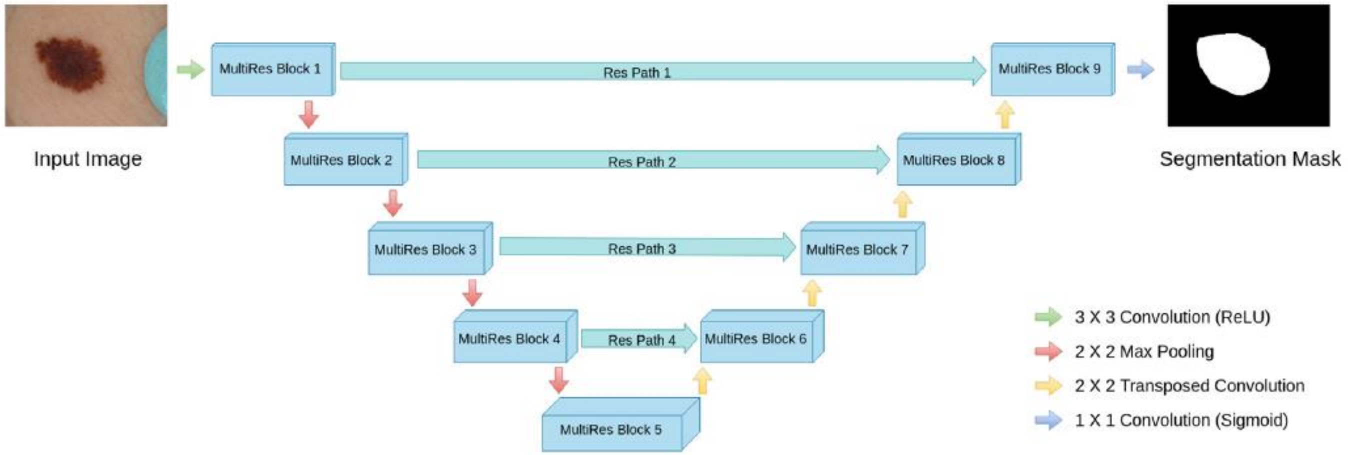
U-Net

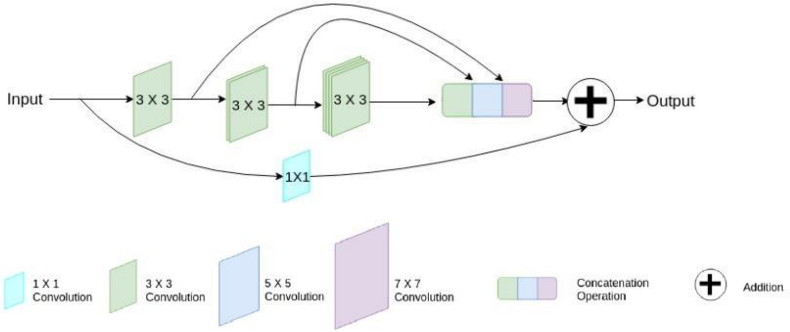
- U-Net is a deep convolutional neural network.
- It has 31.5 million parameters for 2D model and more than 60 million for 3D model.
- It requires large video memory.

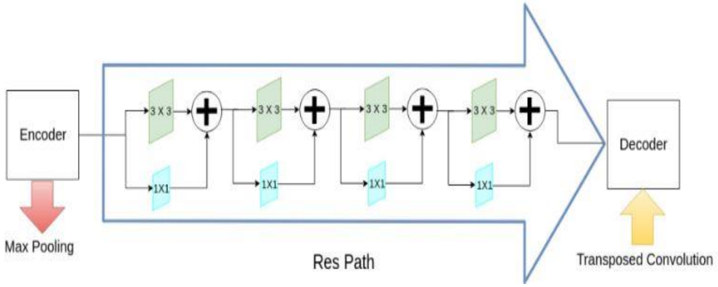


MultiResUnet

- MultiResUnet is a more advanced U-Net based network.
- It has 7.1 million parameters for 2D model and 10.2 for the 3D model.
- It is lighter than the U-Net







2D Dataset

- The applicator used is the spherical.
- The dataset was randomly cropped from a thorax CT scan.
- The dataset include 1118 as training set and 124 validation set.
- The dataset was calculated with the HMC.
- The image size is 128X128 with a pixel size of 0.5mmX0.5mm.
- The training of the 2D models took 30 minutes in average.
- The number of epochs was 200.
- Batch size was 2.

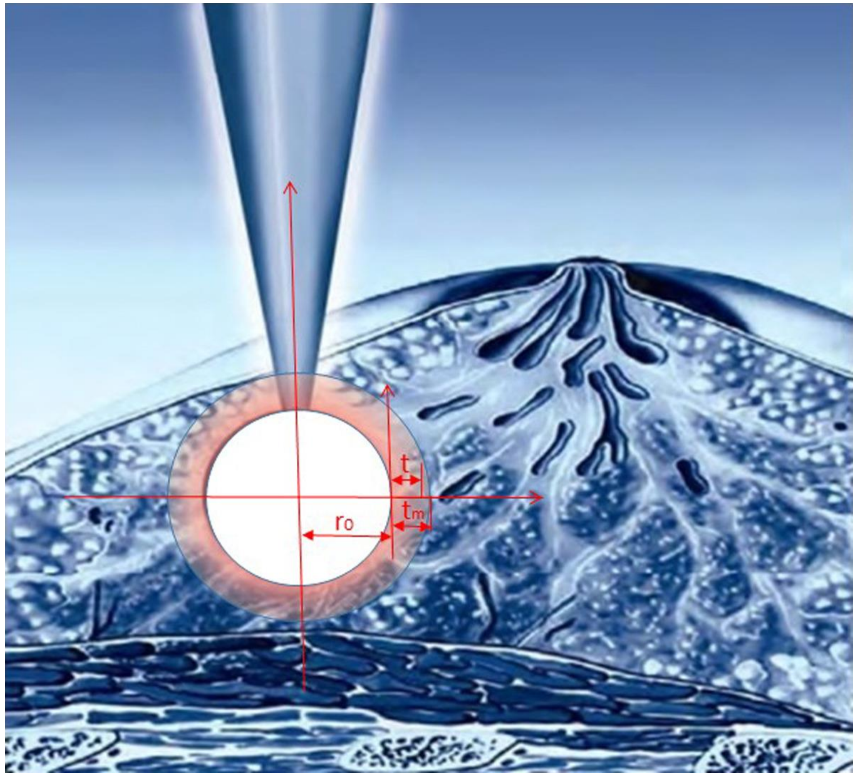
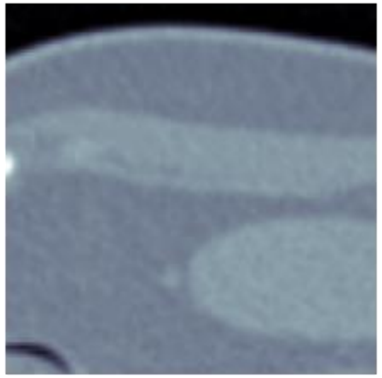


Image extracted from the AAPM webpage

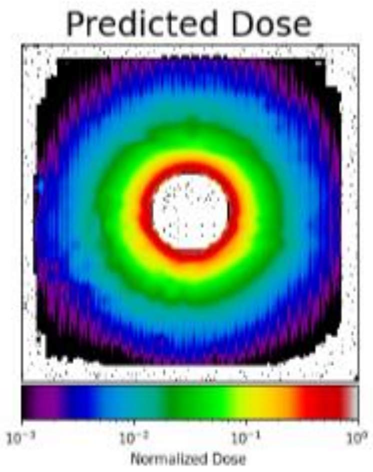
Deep Learning for INTRABEAM

Input of the Neural Network

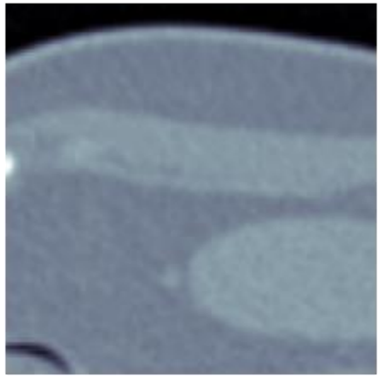
CT



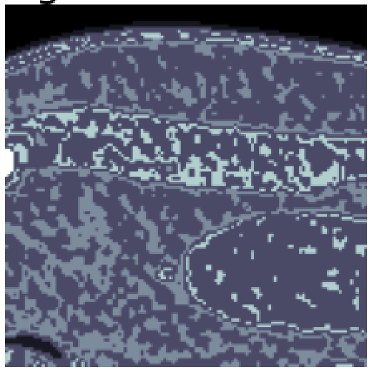
Neural Network



CT



Segmentation mask



Neural Network