



Behind the Beam: Towards Smart BNCT Treatment Planning

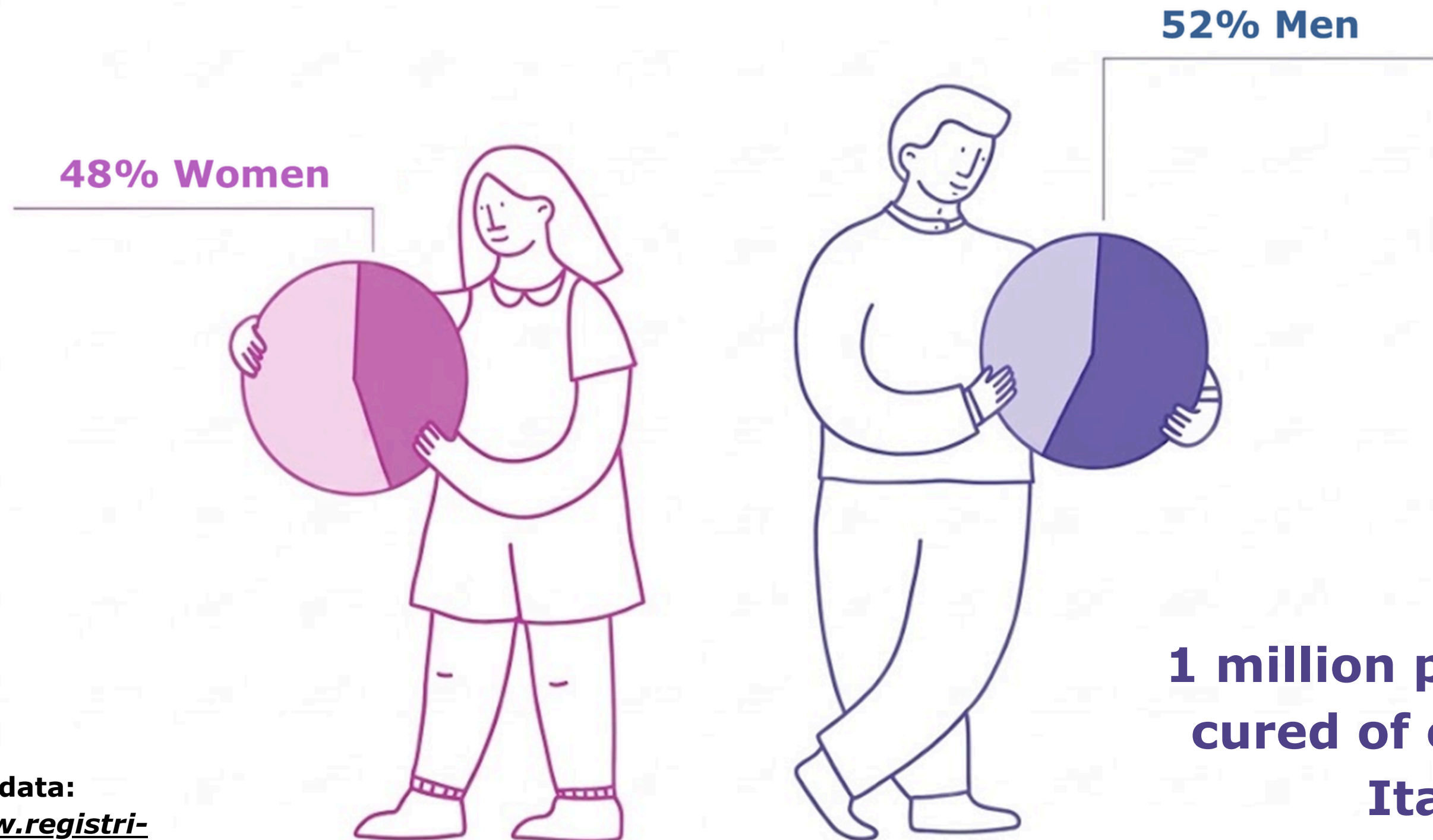
PhD Student: Cristina Pezzi

XL Cycle

Supervisors: Prof.ssa Silva Bortolussi, Prof. Ian Postuma



377.000 new diagnosis in Italy



**1 million people are
cured of cancer in
Italy**

Official data:
<https://www.registri-tumori.it/cms/pubblicazioni/i-numeri-del-cancro-italia-2020>

Radiotherapy

Chemotherapy

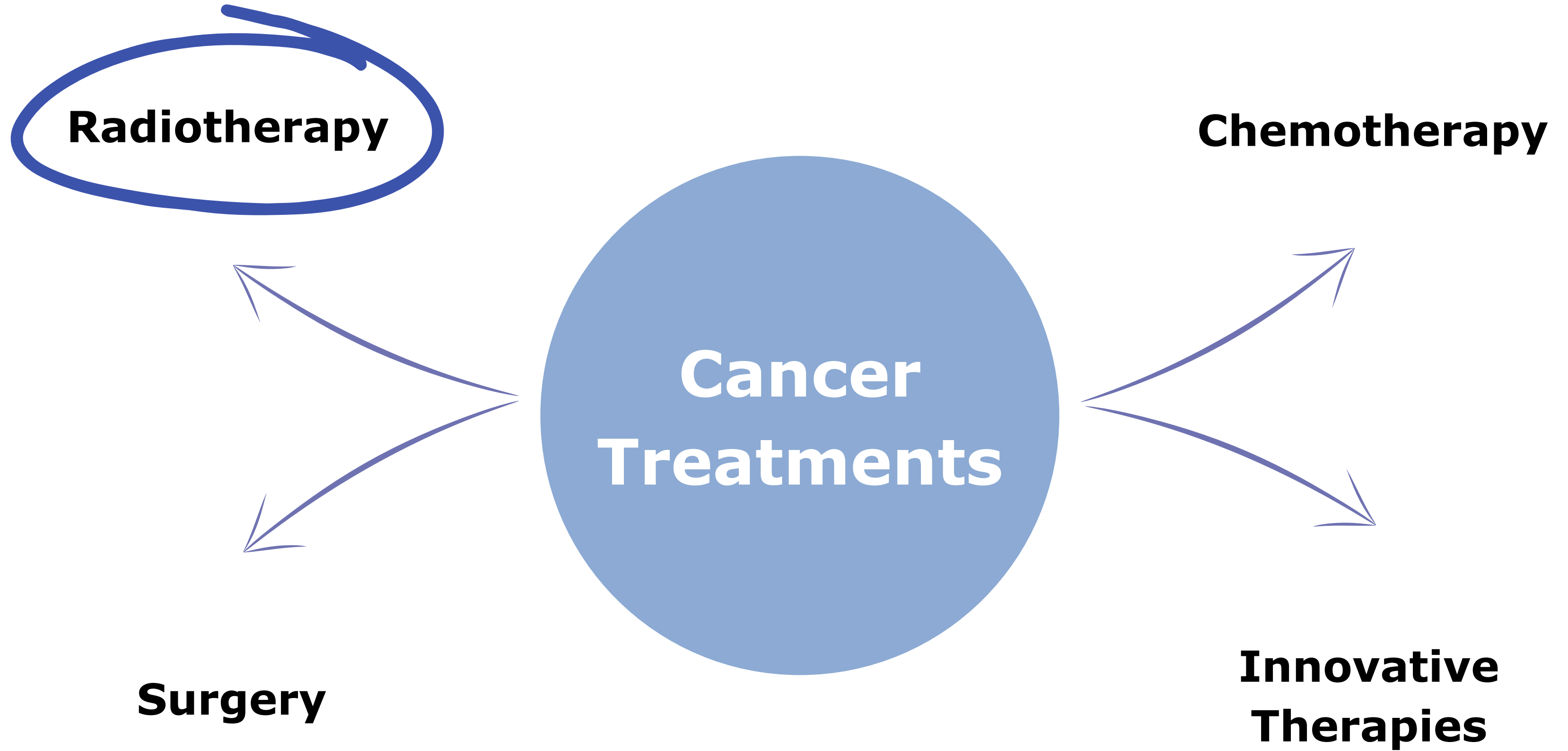
**Cancer
Treatments**



```
graph LR; CT((Cancer Treatments)) --> R[Radiotherapy]; CT --> S[Surgery]; CT --> C[Chemotherapy]; CT --> IT[Innovative Therapies];
```

Surgery

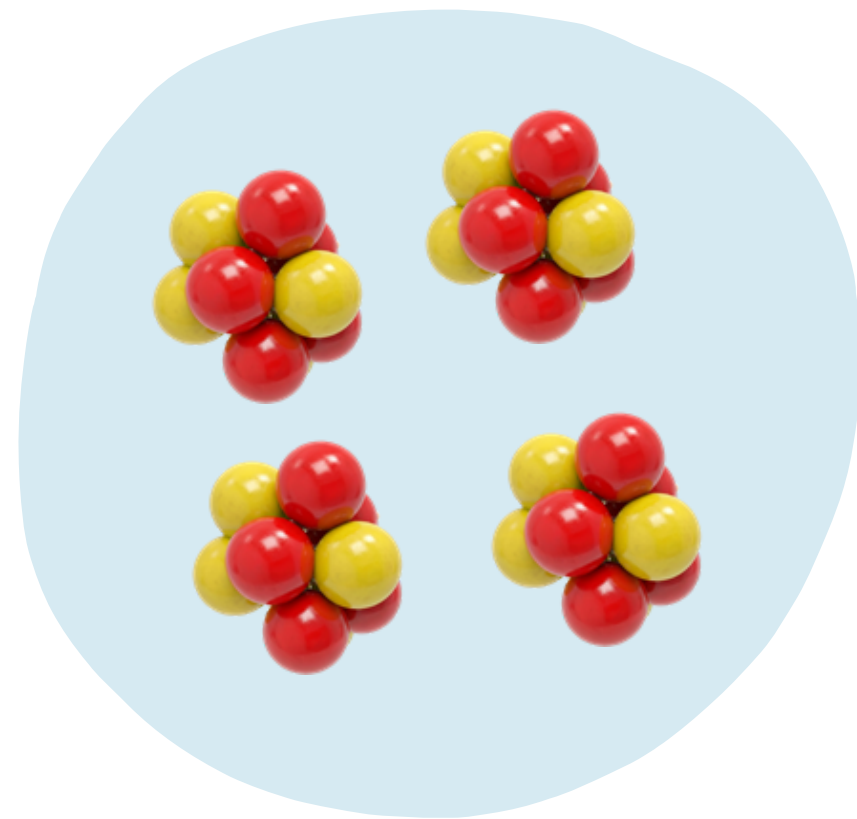
**Innovative
Therapies**



Boron Neutron Capture Therapy



Boron Neutron Capture Therapy



**Boron-10
atoms**



Boron Neutron Capture Therapy

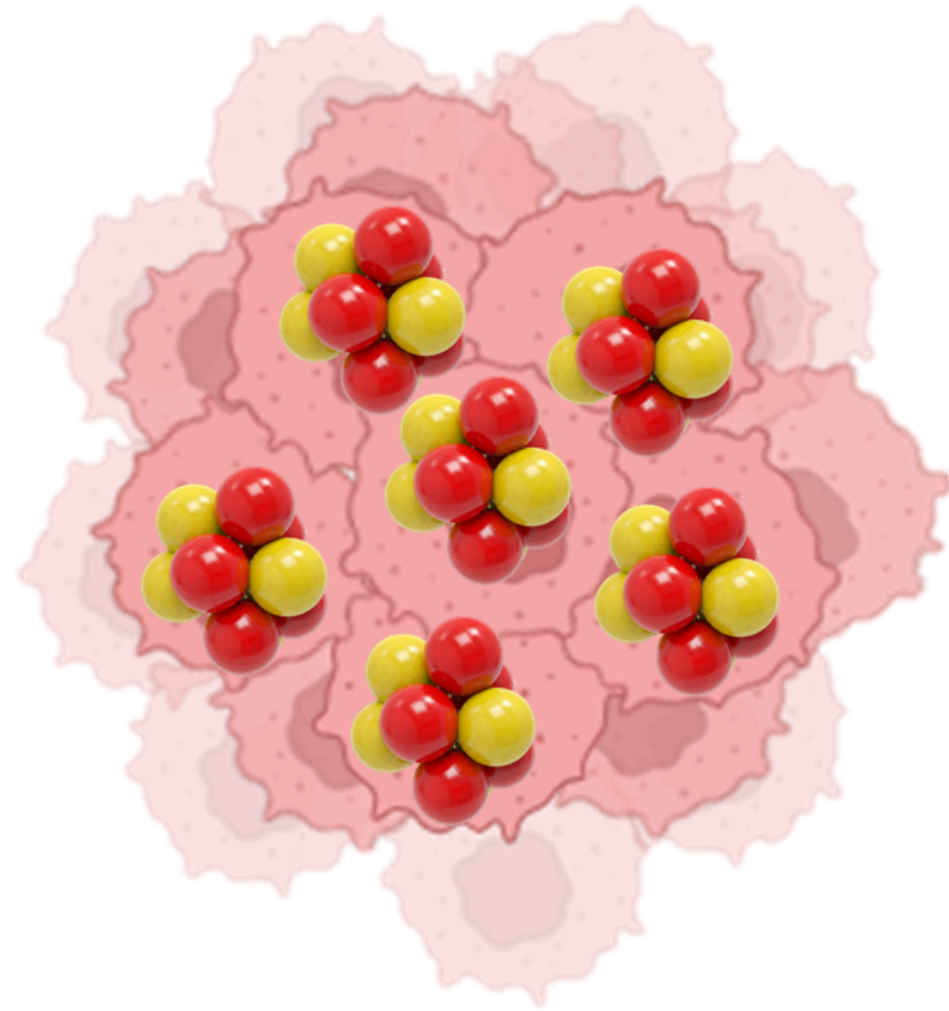
Thermal
Neutron
Beam



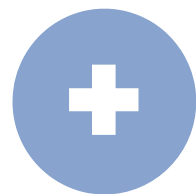
Boron Neutron Capture Therapy



Boron Neutron Capture Therapy

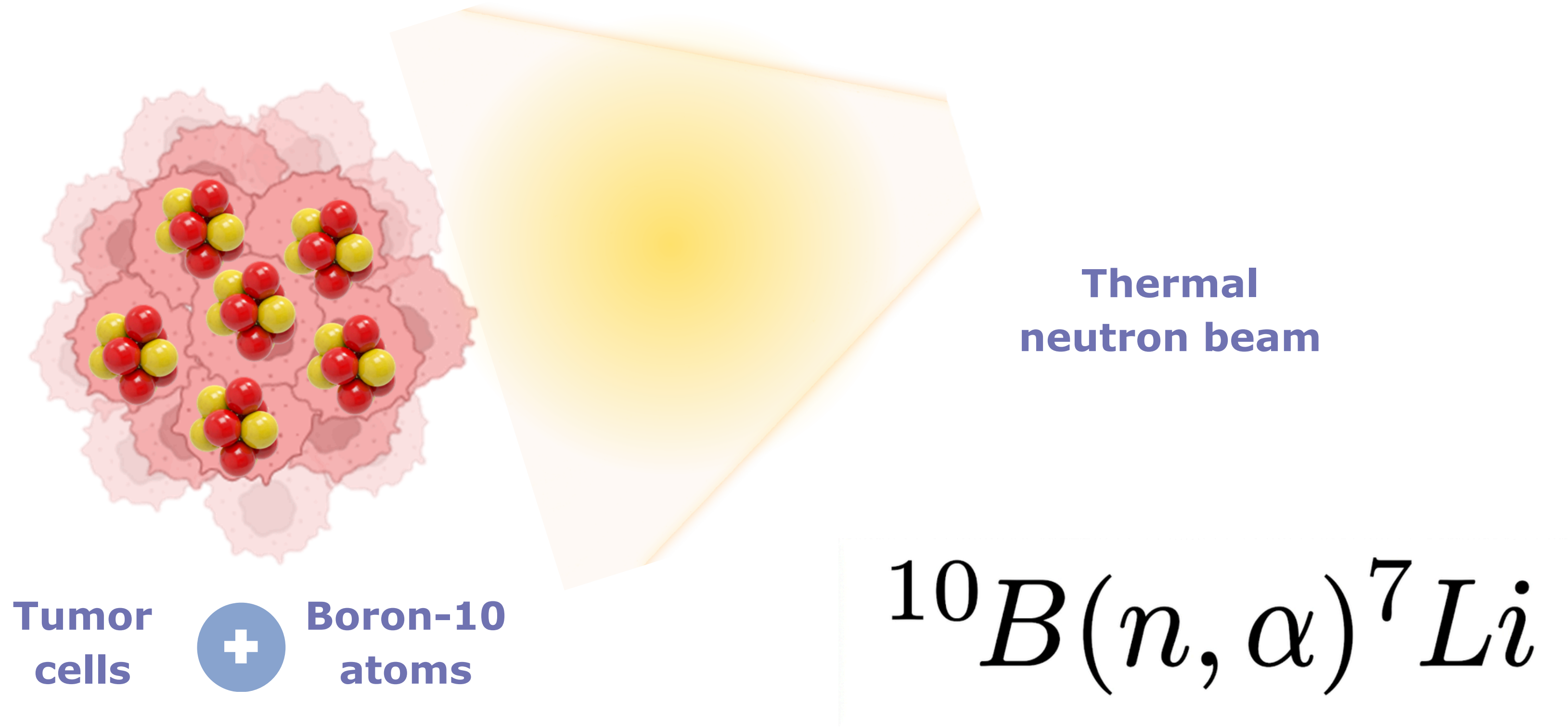


**Tumor
cells**



**Boron-10
atoms**

Boron Neutron Capture Therapy



Boron Neutron Capture Therapy

**High Linear Energy
Transfer (LET) Radiations**

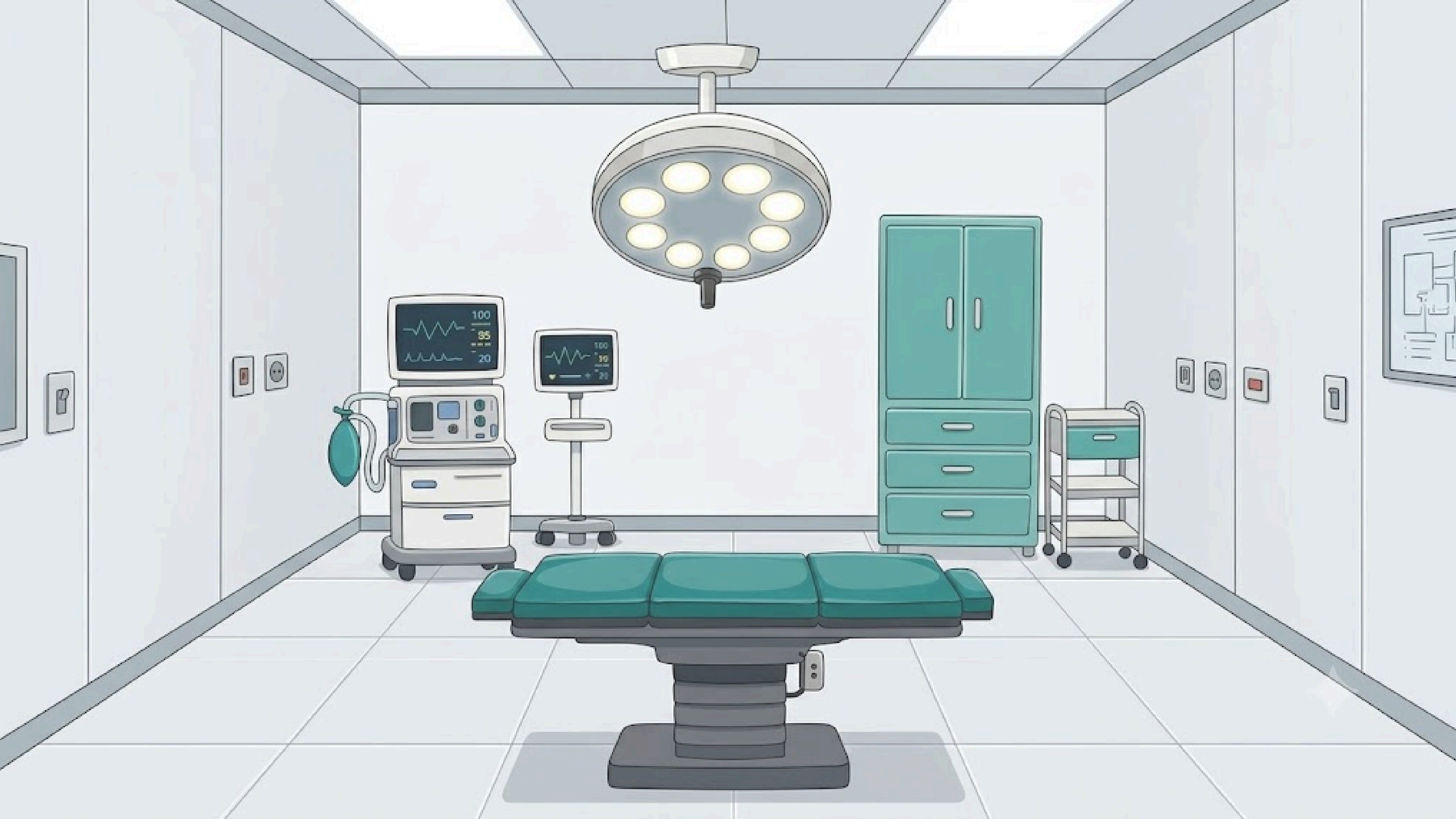
**High Selectivity
High Efficacy**

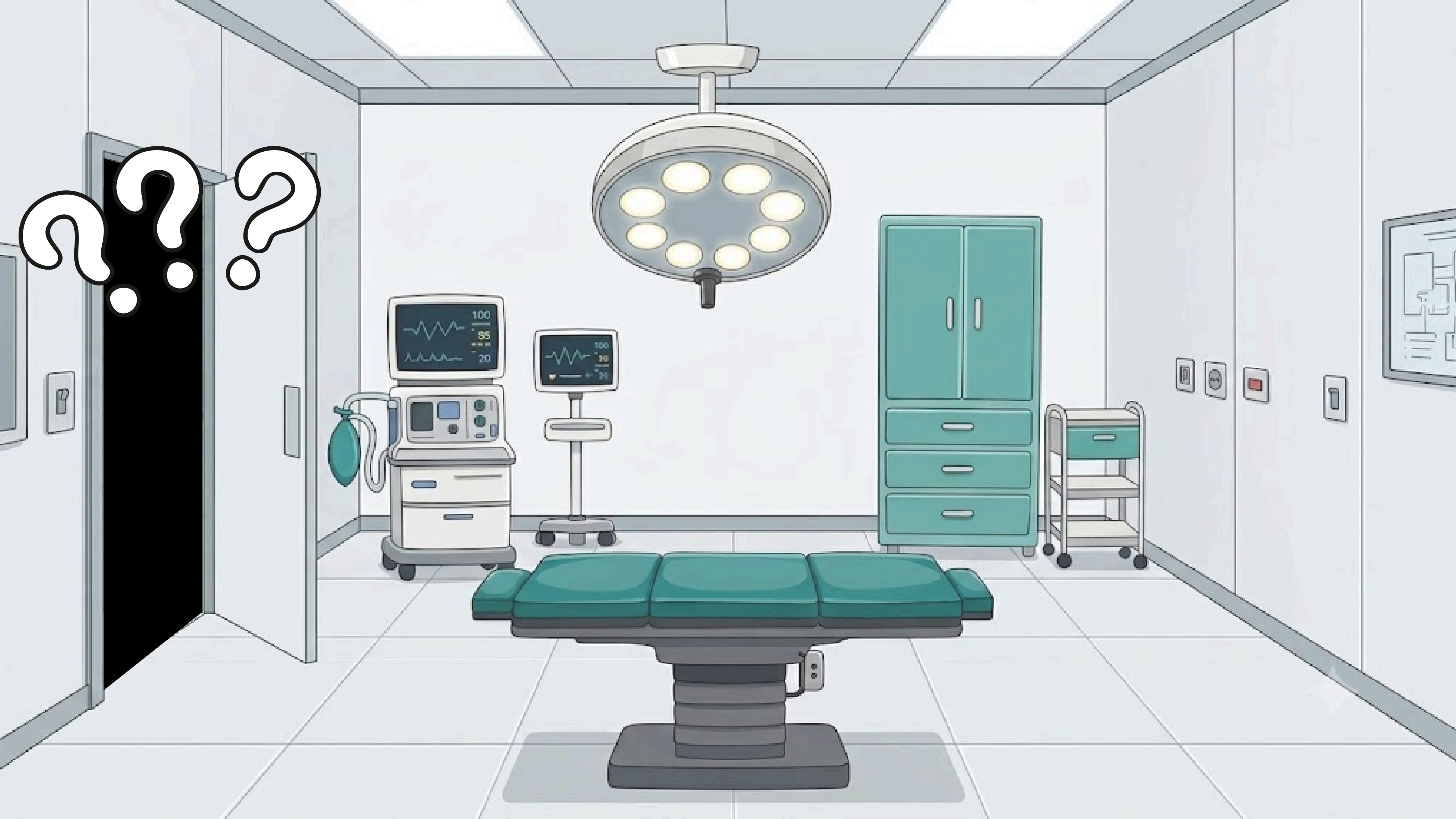
Tumor
cells



Boron-10
atoms







TREATMENT PLANNING SYSTEM

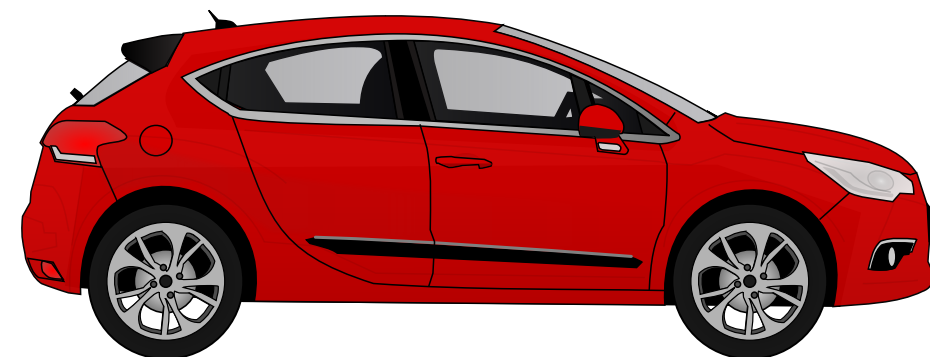
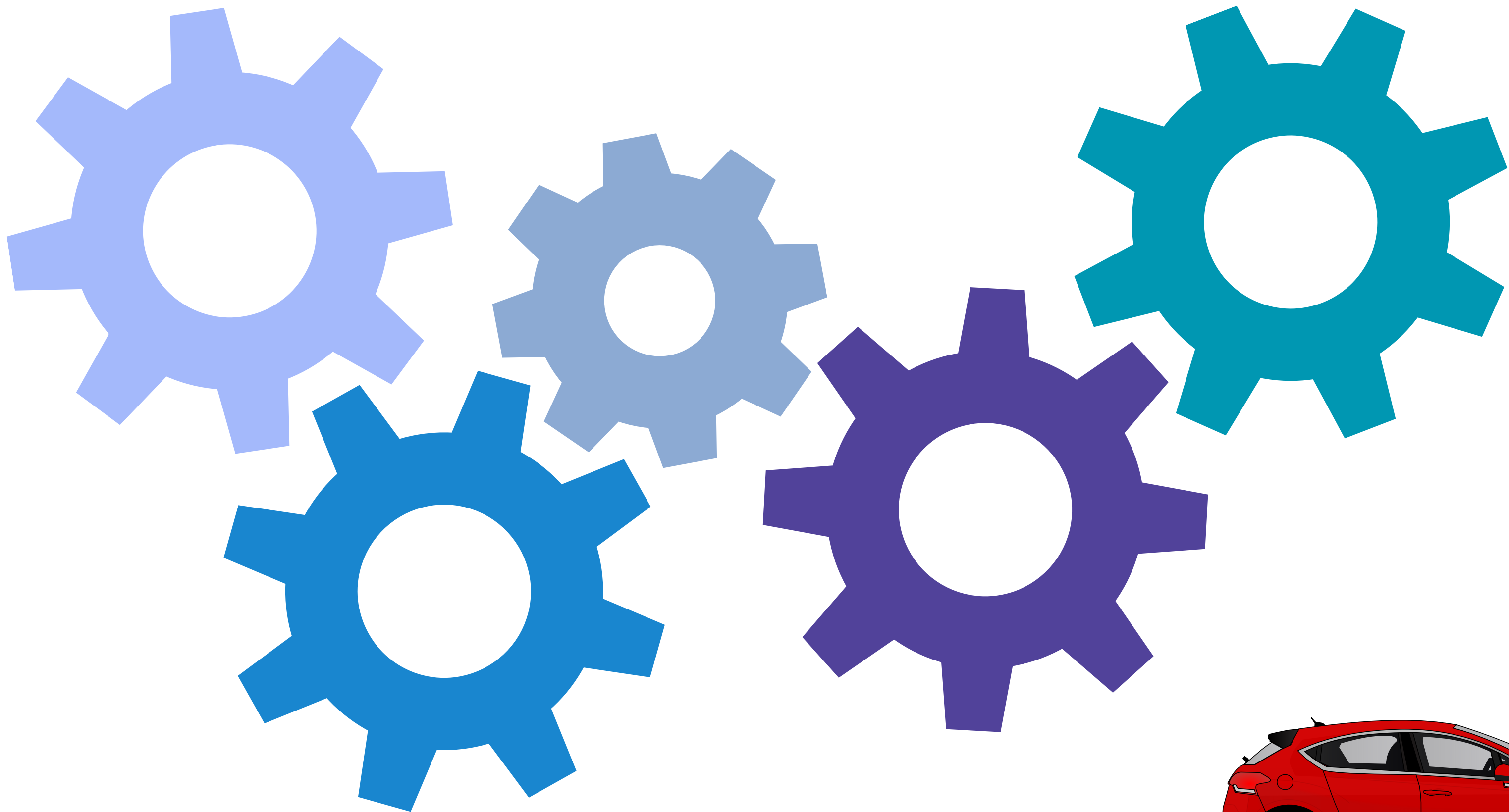
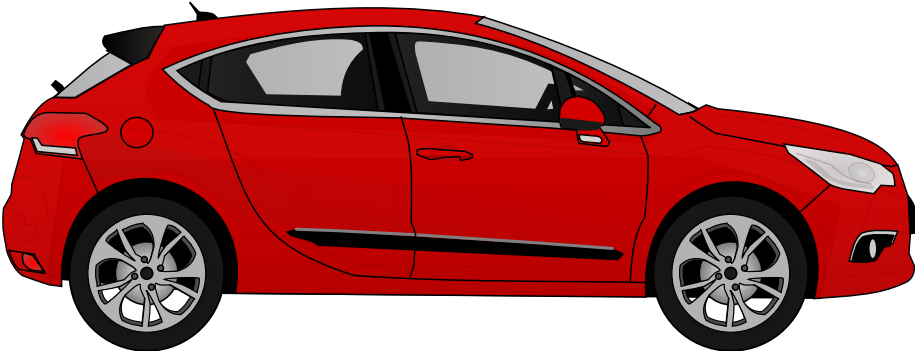
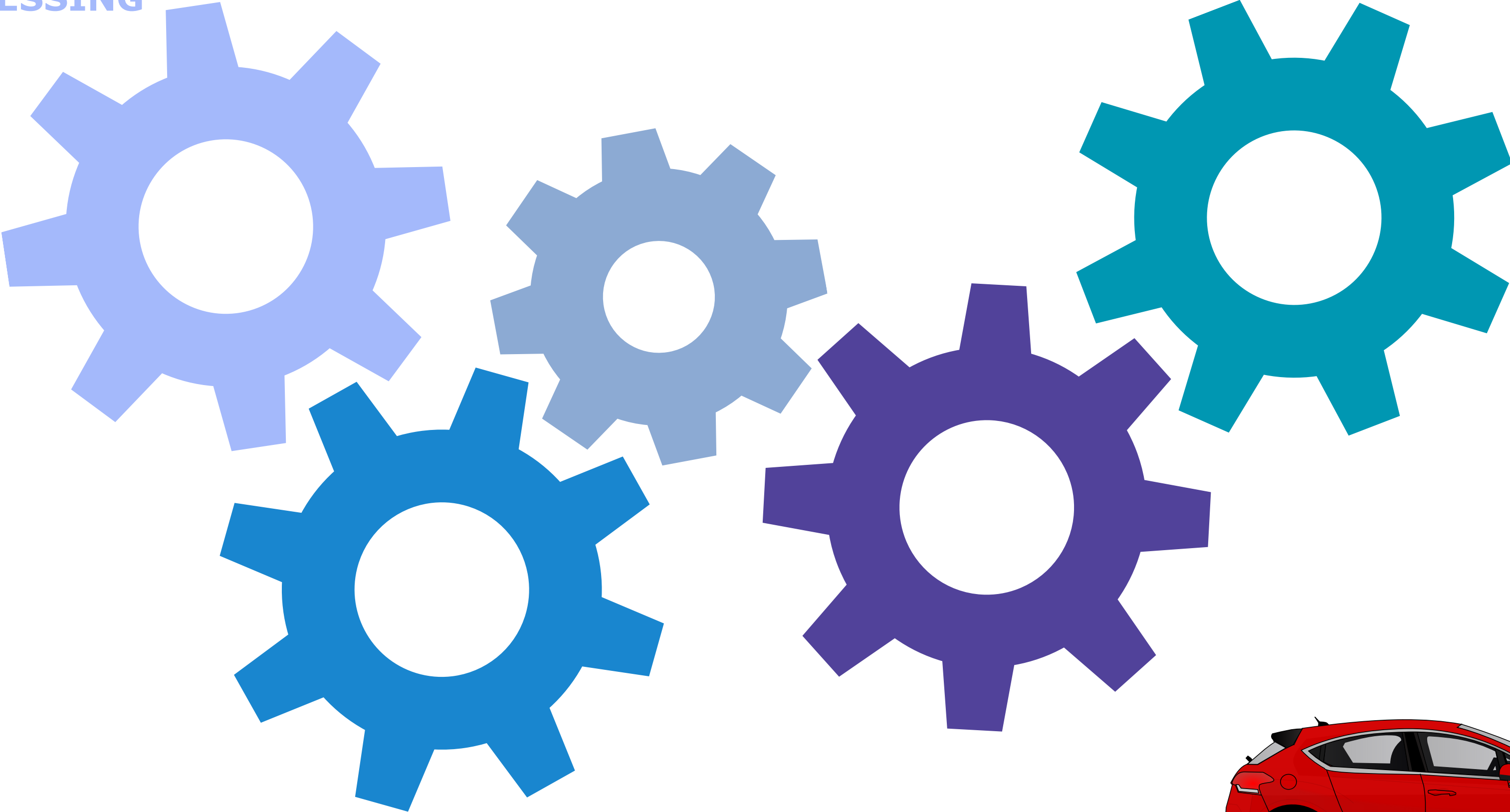
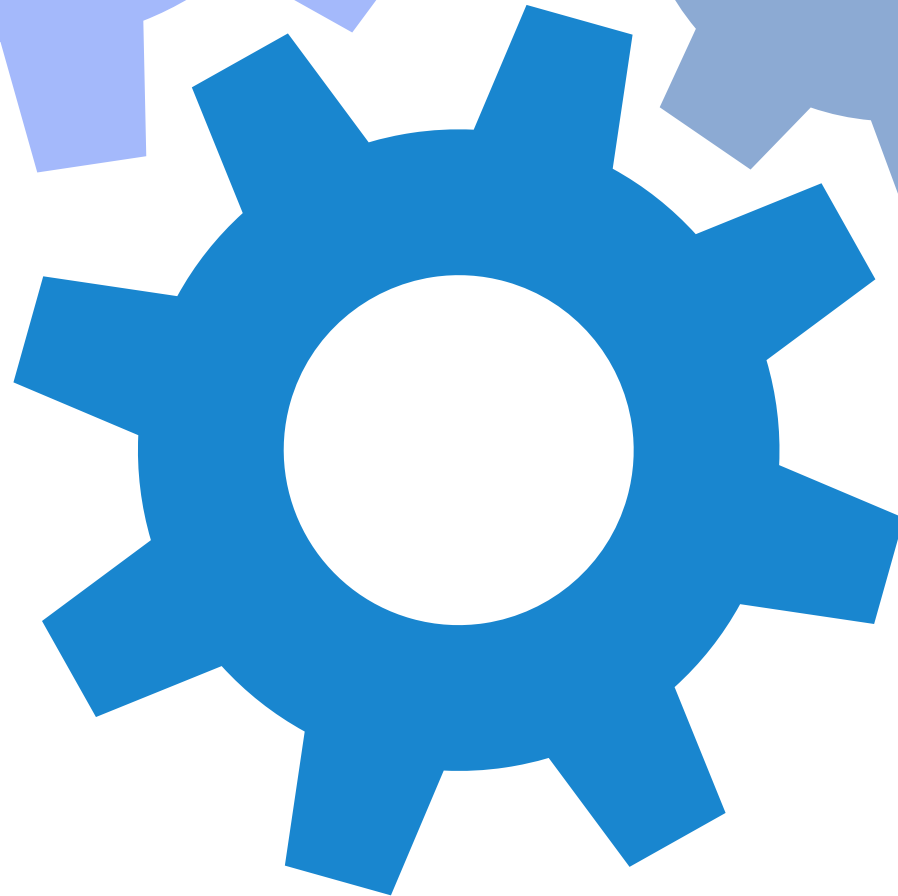
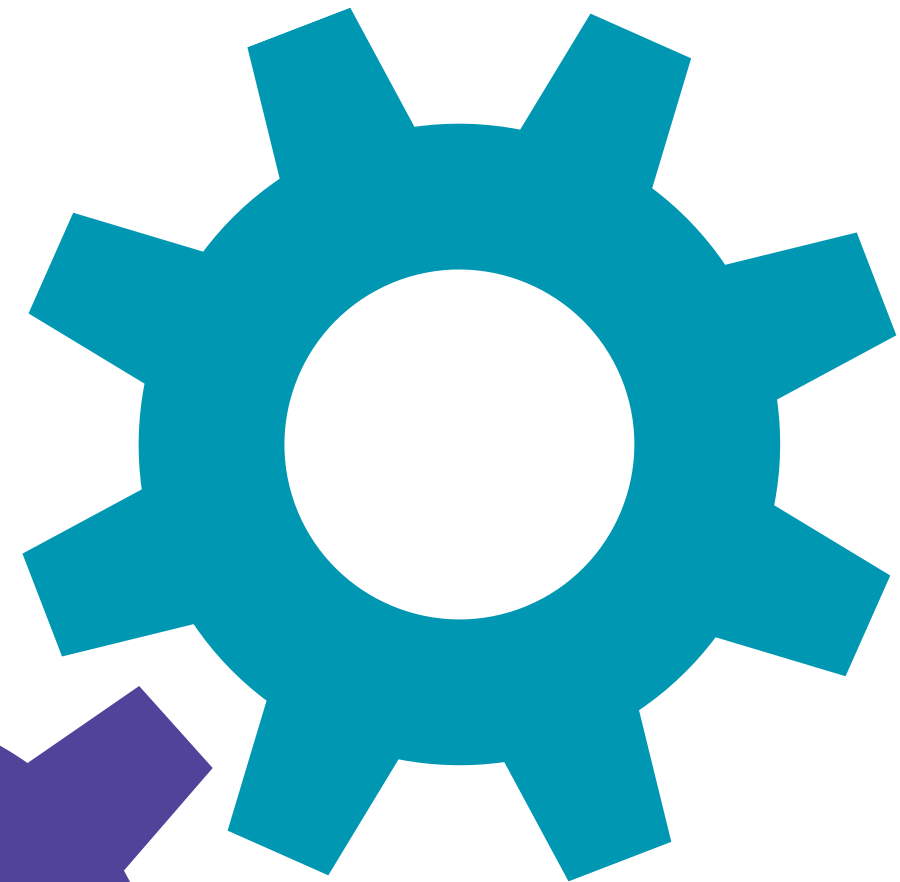
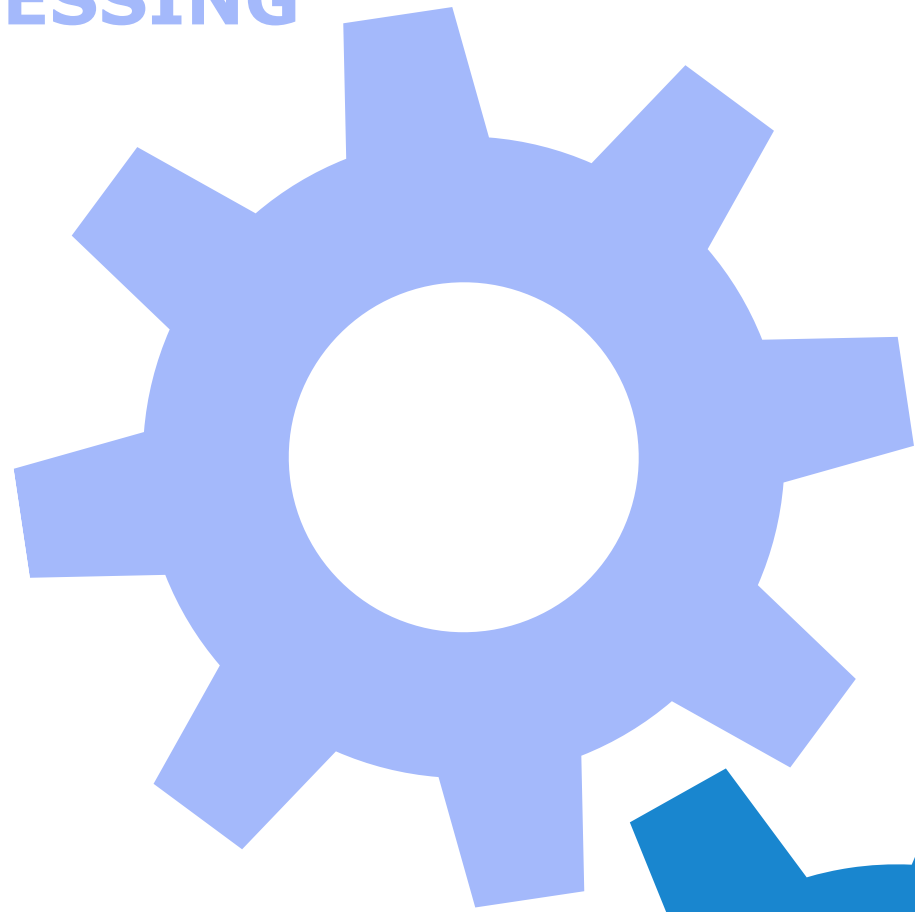


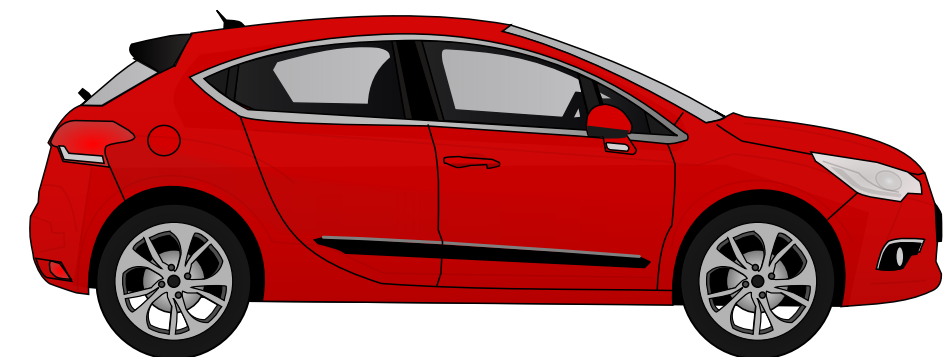
IMAGE
PROCESSING



**IMAGE
PROCESSING**



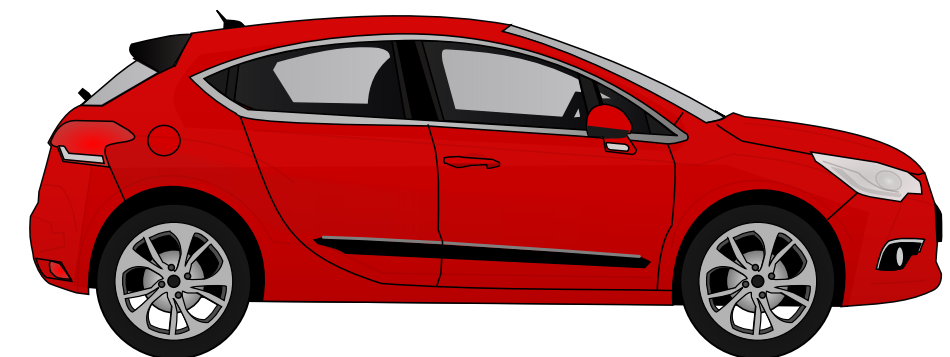
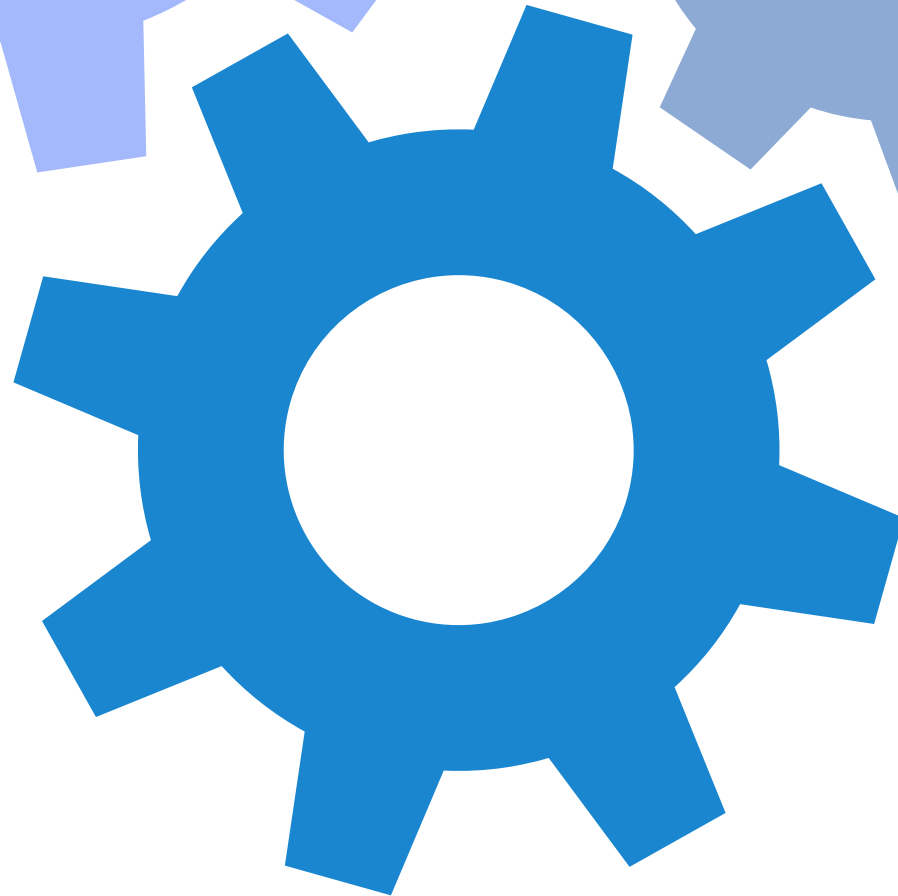
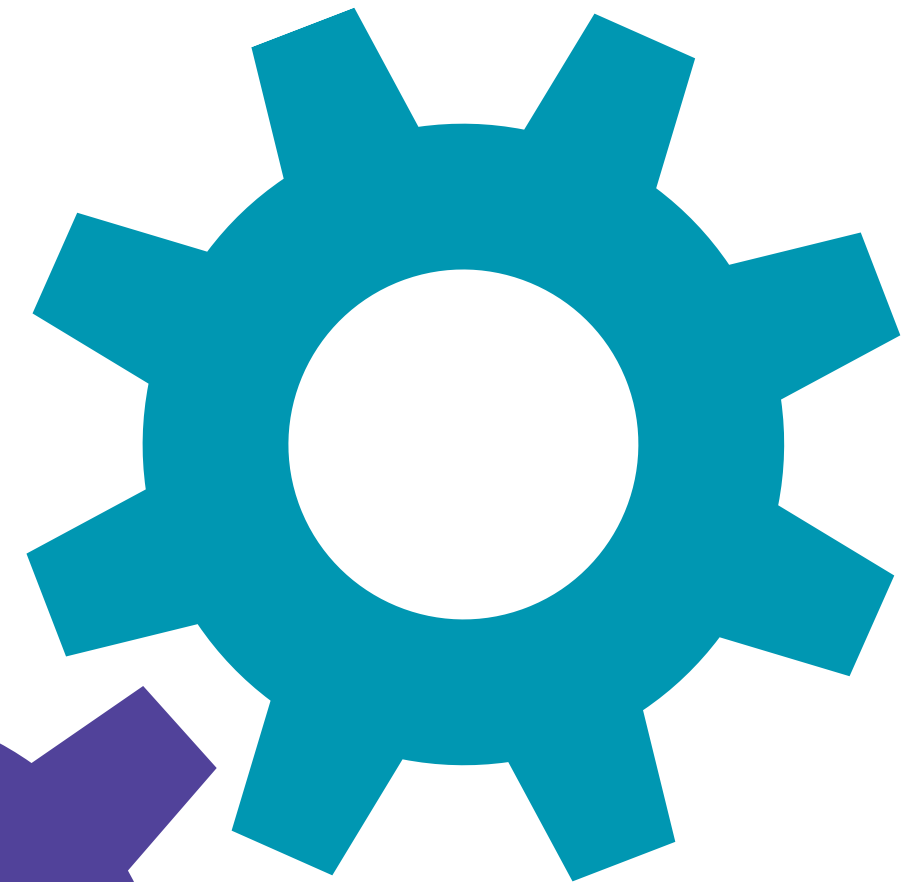
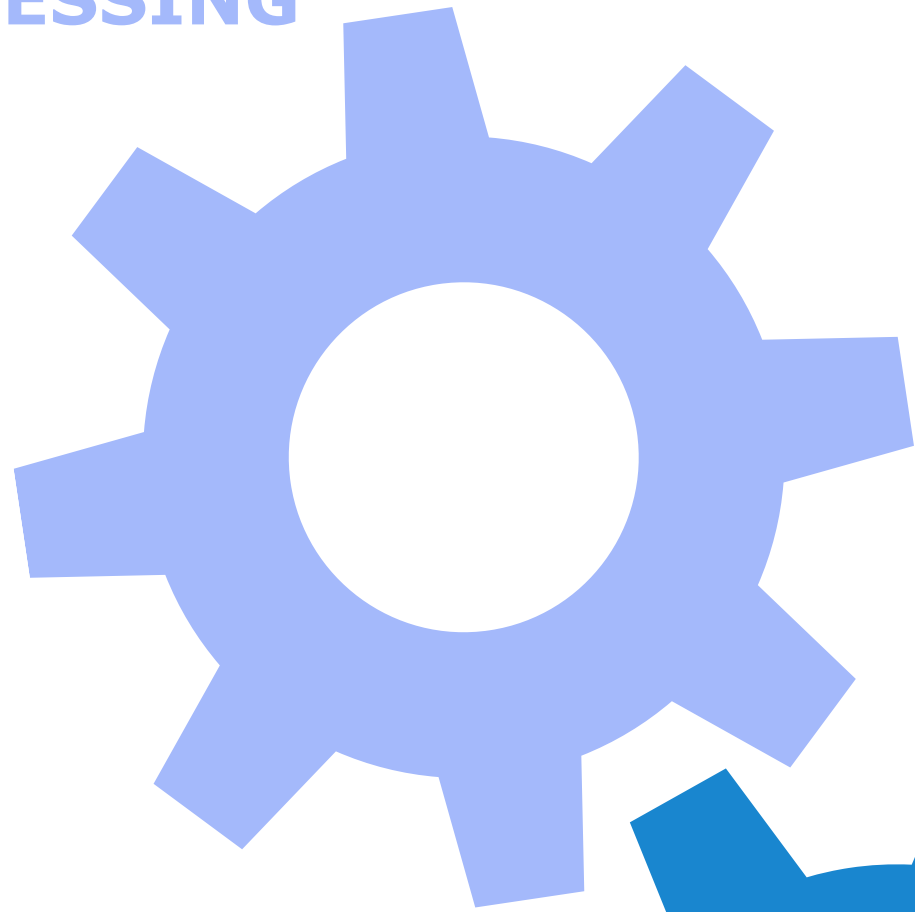
**REGION OF
INTEREST
IDENTIFICATION**



**IMAGE
PROCESSING**

PATIENT MODELING

**REGION OF
INTEREST
IDENTIFICATION**

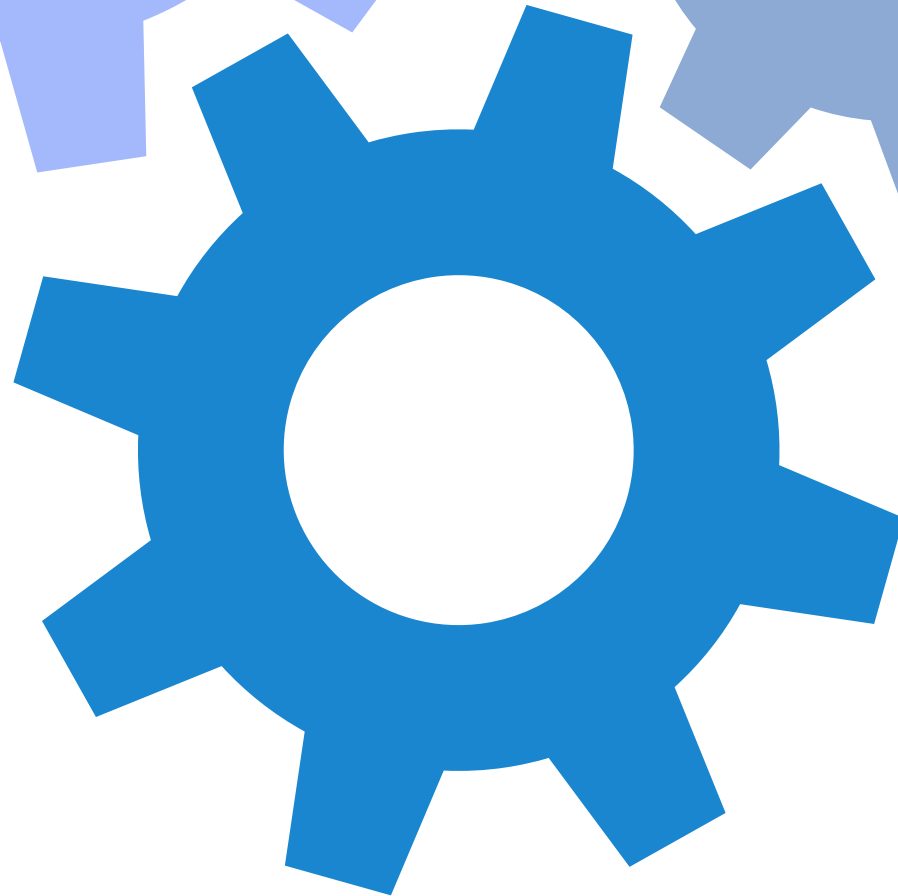
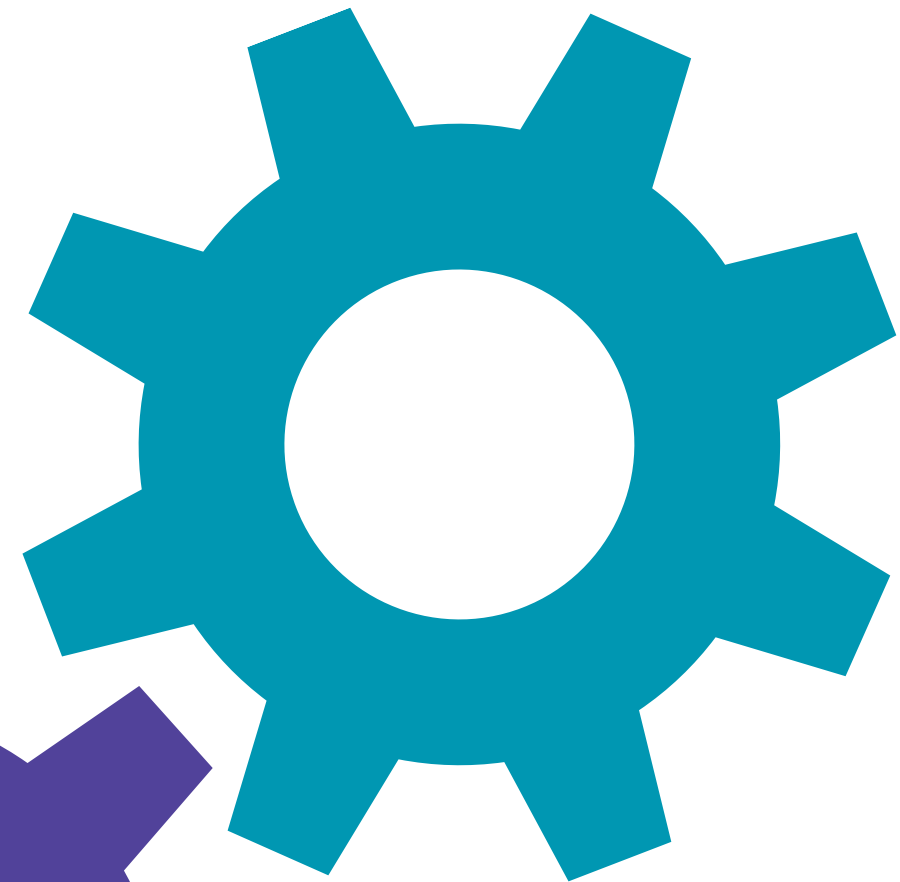
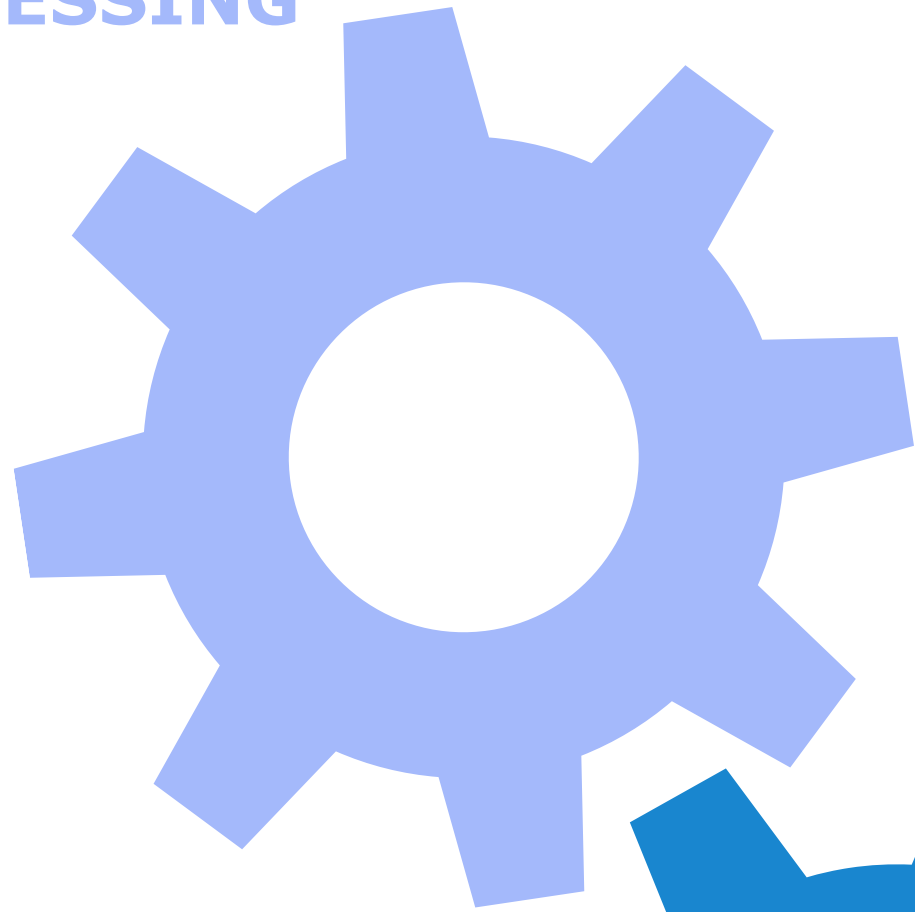
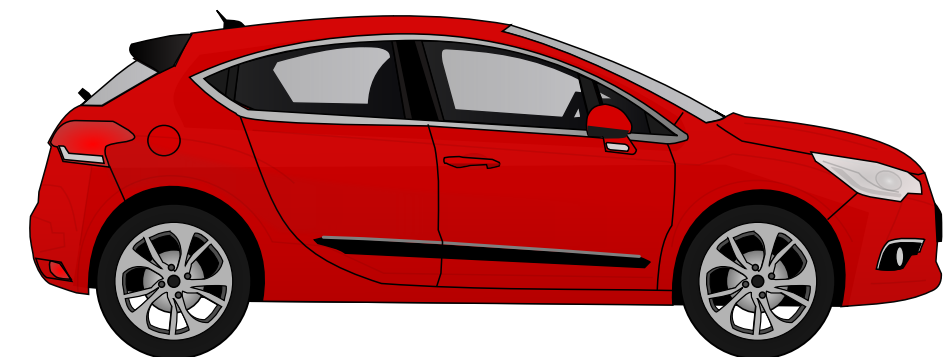


**IMAGE
PROCESSING**

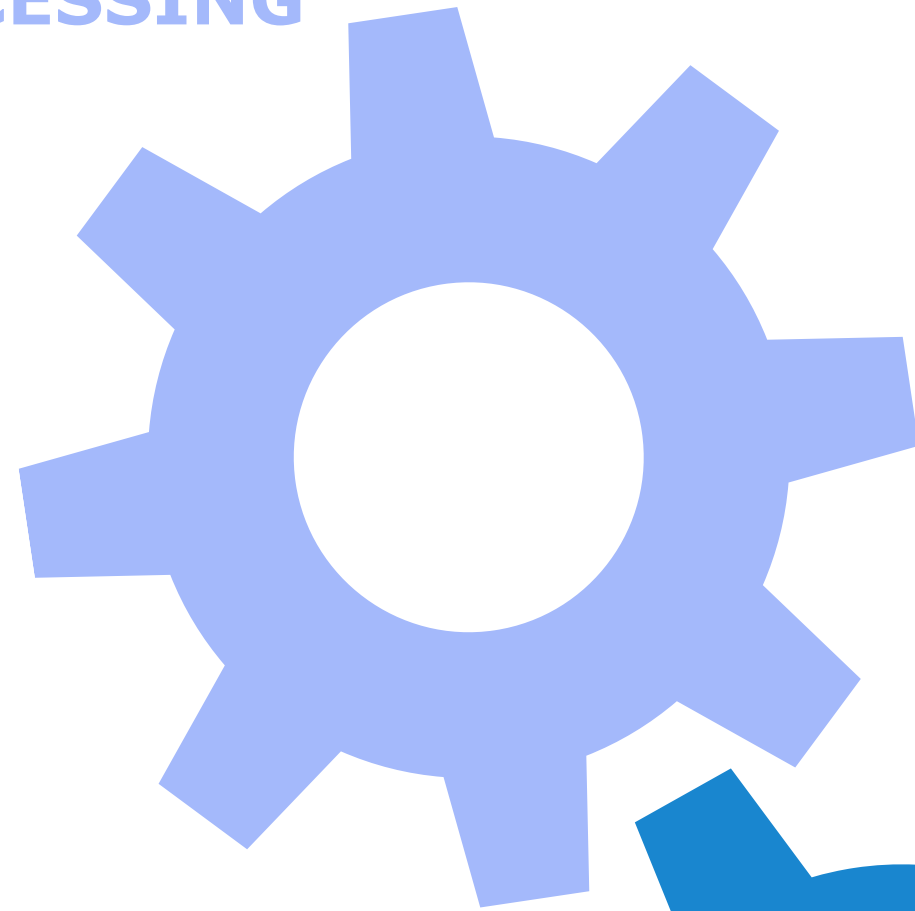
PATIENT MODELING

**REGION OF
INTEREST
IDENTIFICATION**

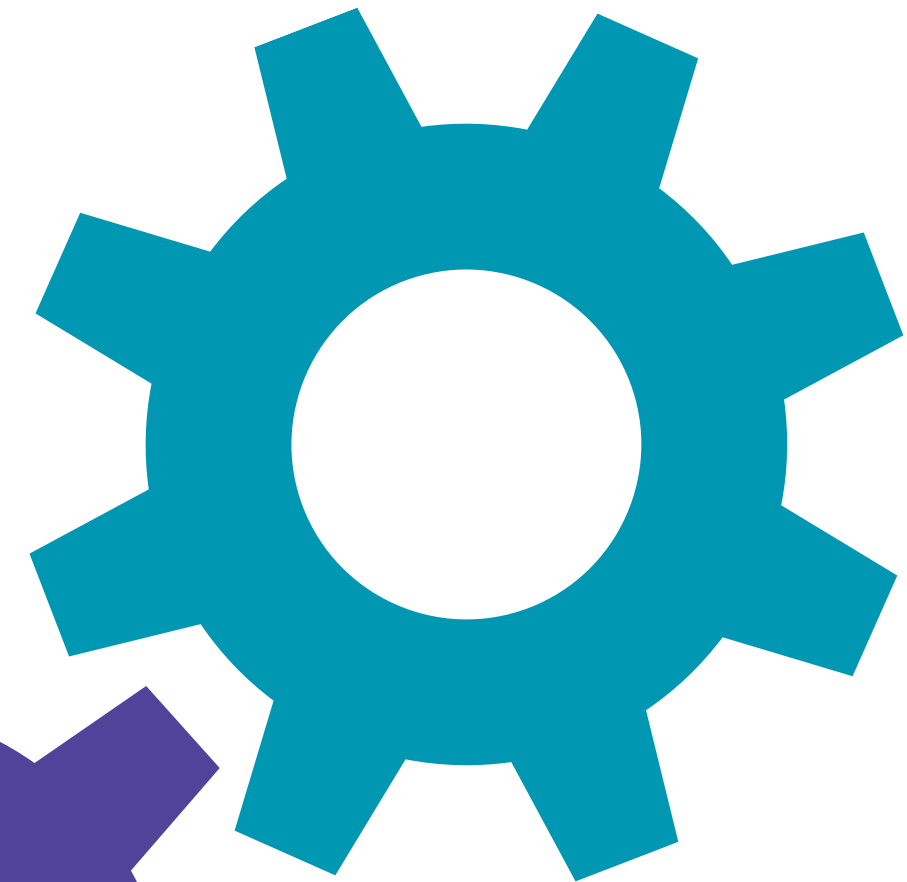
**MONTE CARLO
SIMULATIONS**



**IMAGE
PROCESSING**

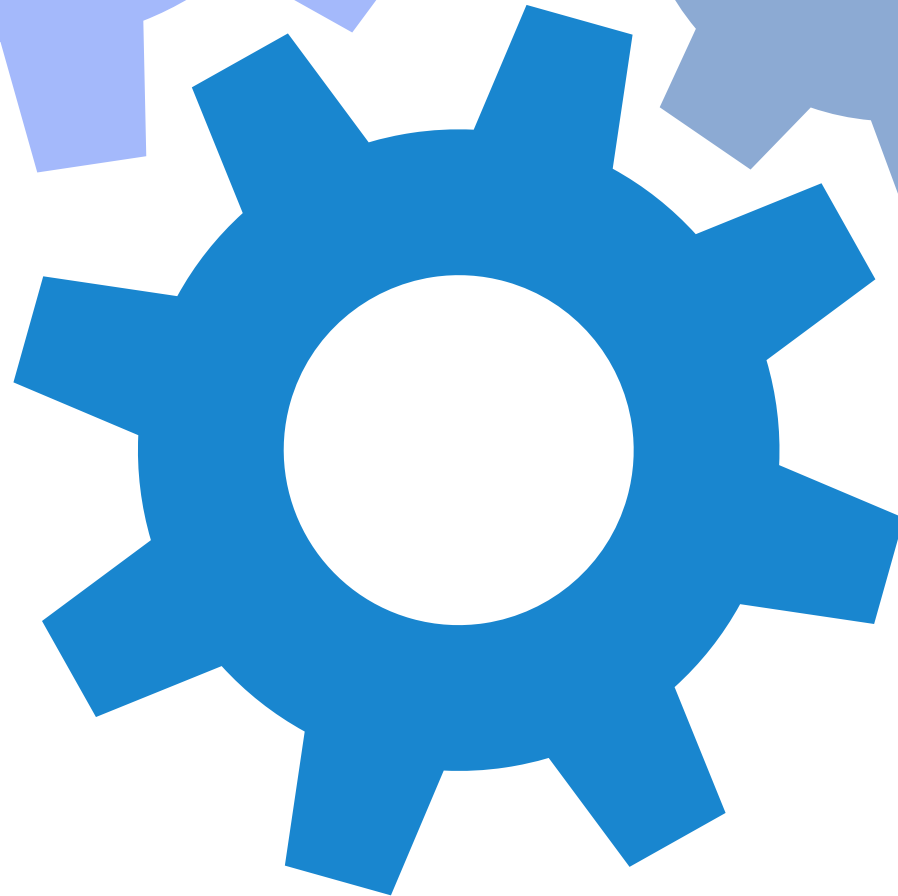


PATIENT MODELING

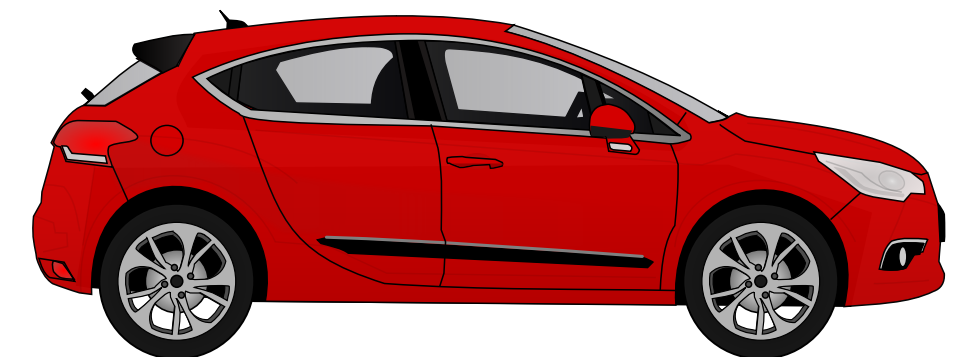


**DOSIMETRIC
ANALYSIS**

**REGION OF
INTEREST
IDENTIFICATION**



**MONTE CARLO
SIMULATIONS**



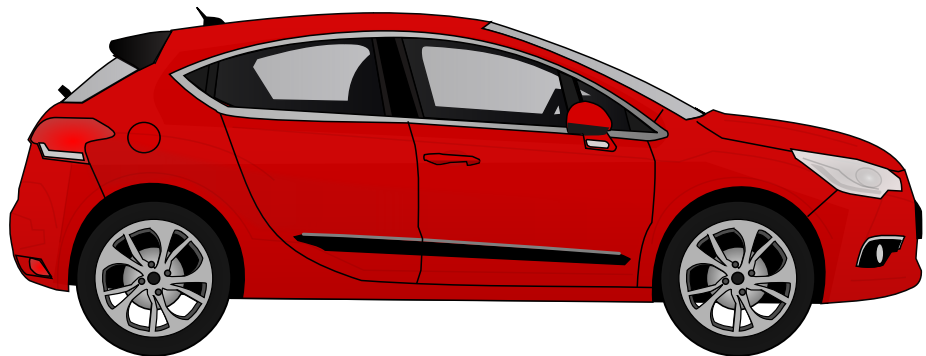
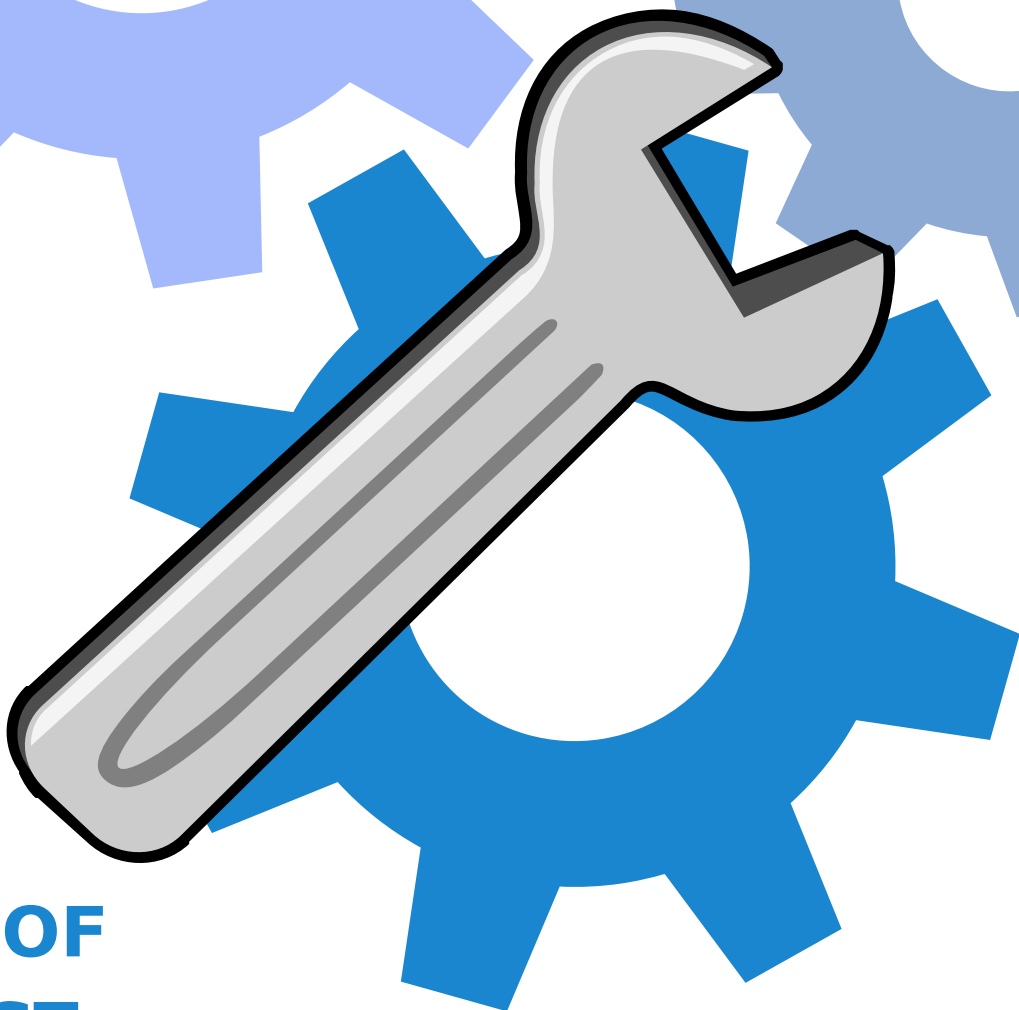
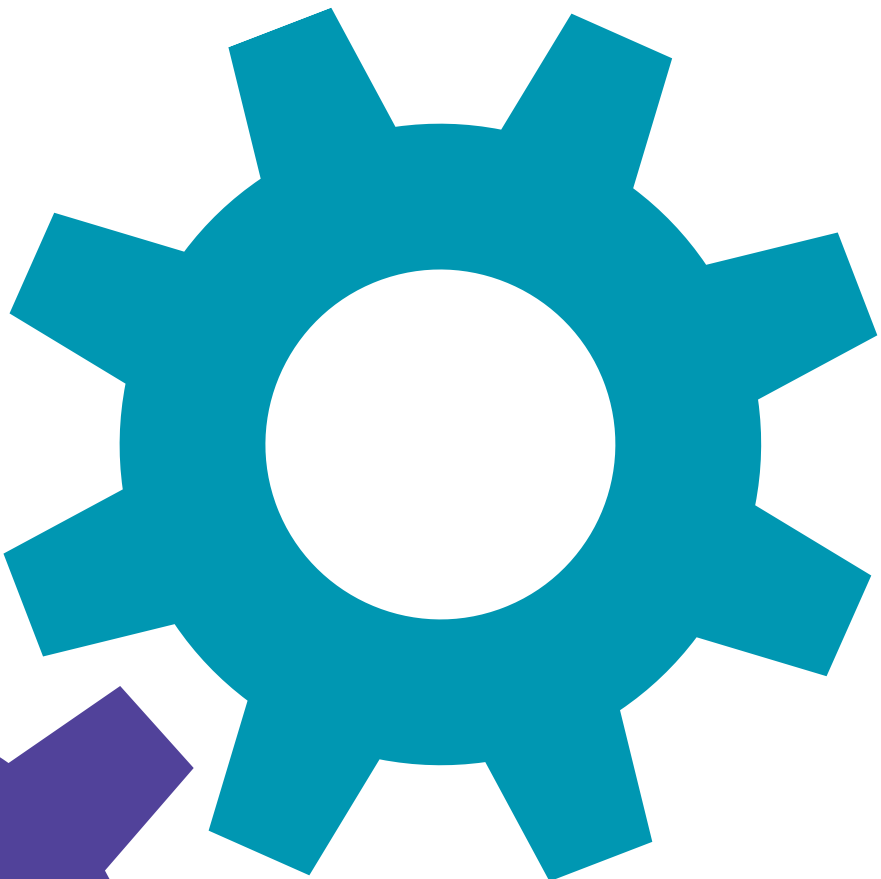
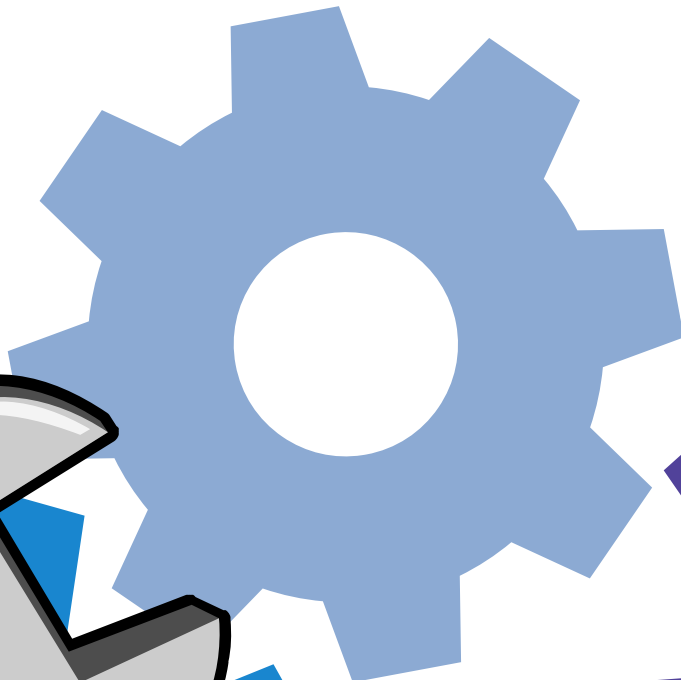
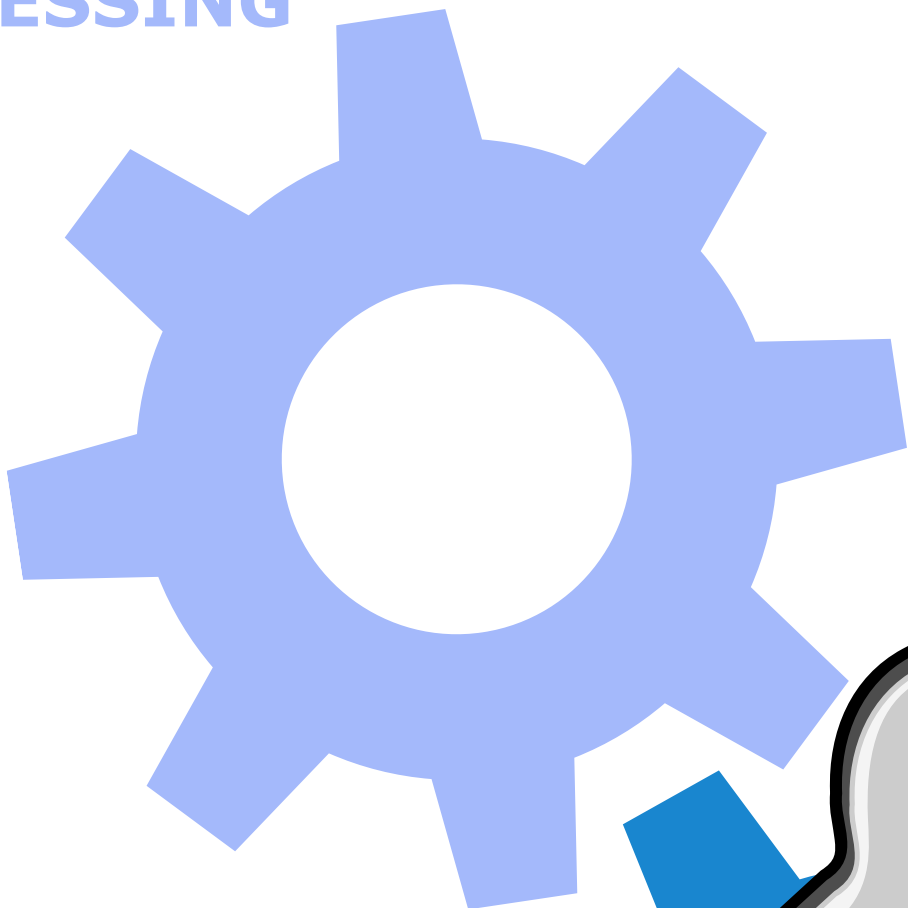
**IMAGE
PROCESSING**

PATIENT MODELING

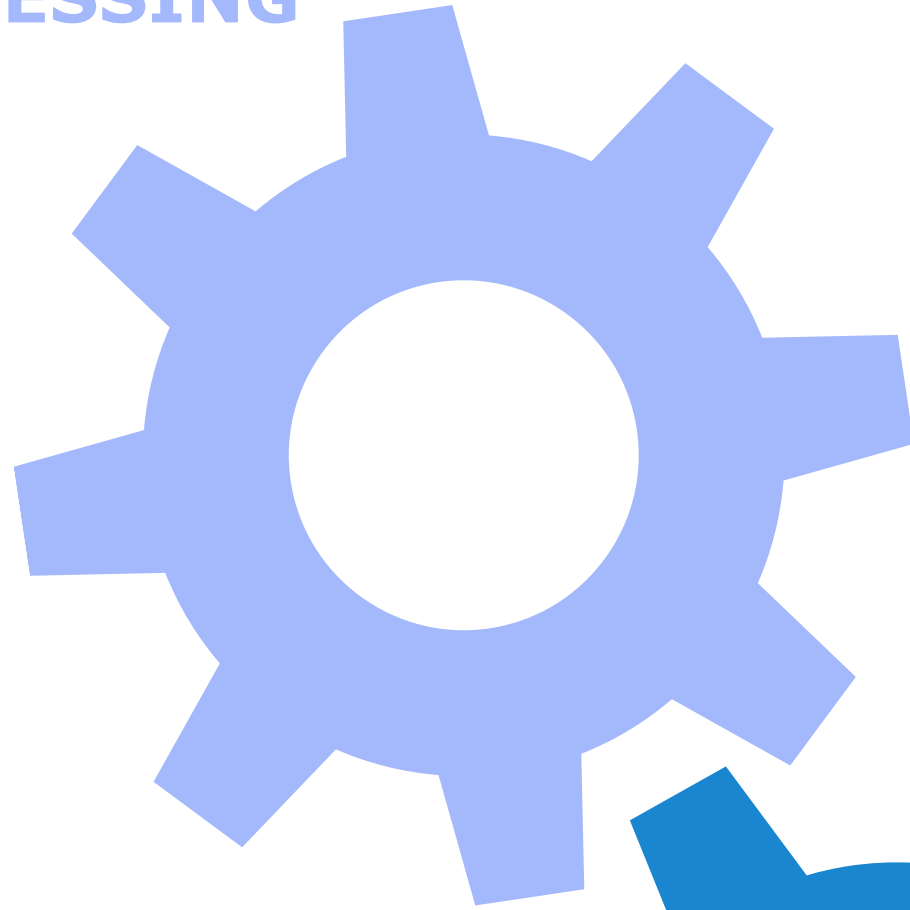
**DOSIMETRIC
ANALYSIS**

**REGION OF
INTEREST
IDENTIFICATION**

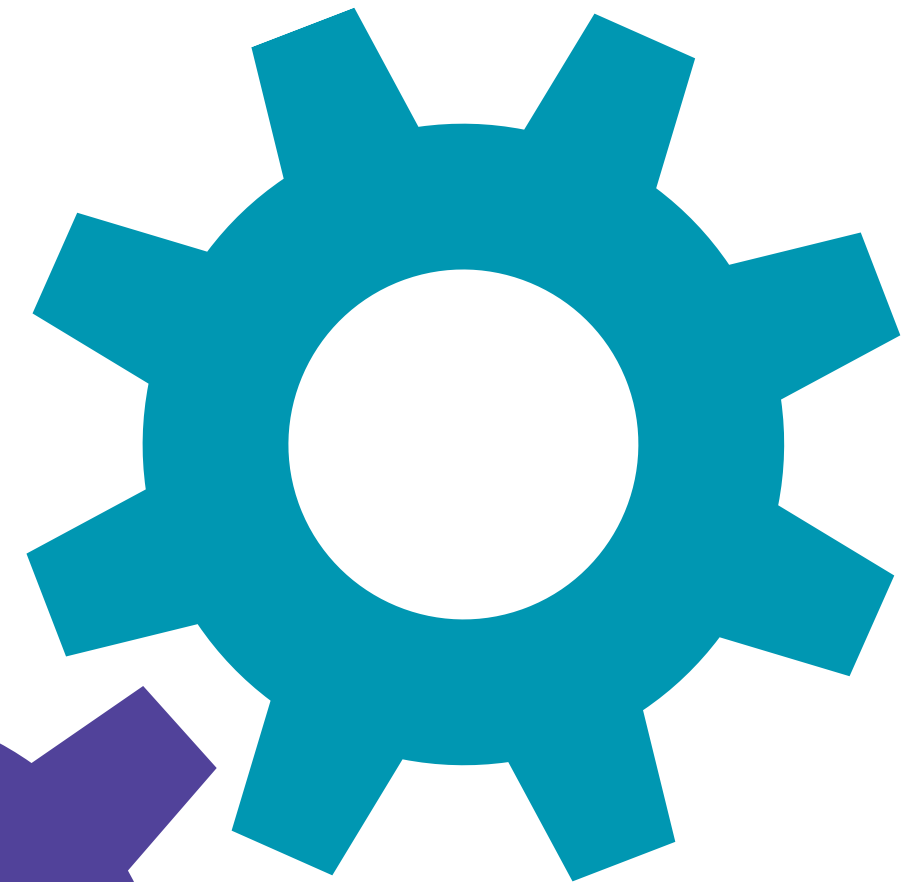
**MONTE CARLO
SIMULATIONS**



**IMAGE
PROCESSING**

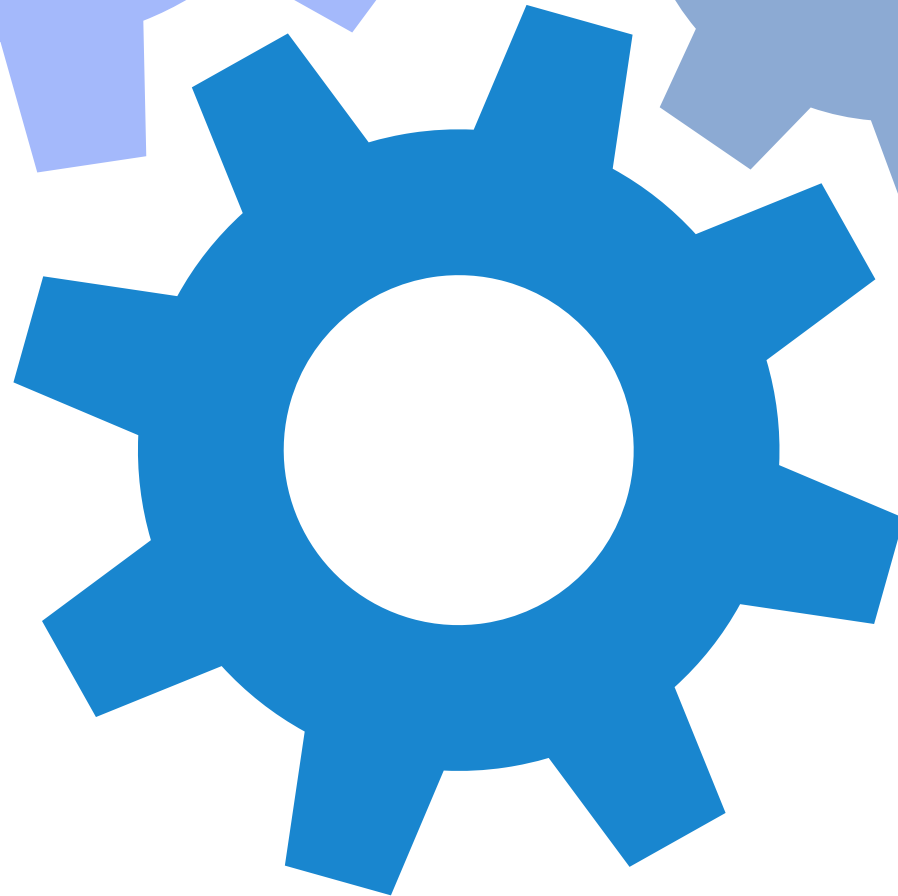


PATIENT MODELING

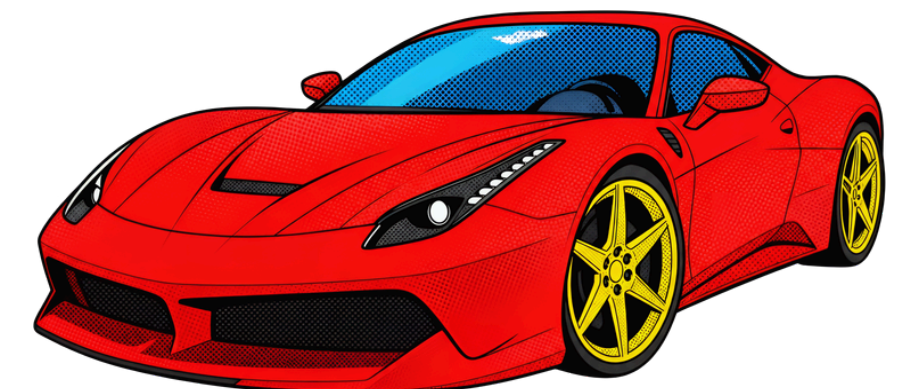


**DOSIMETRIC
ANALYSIS**

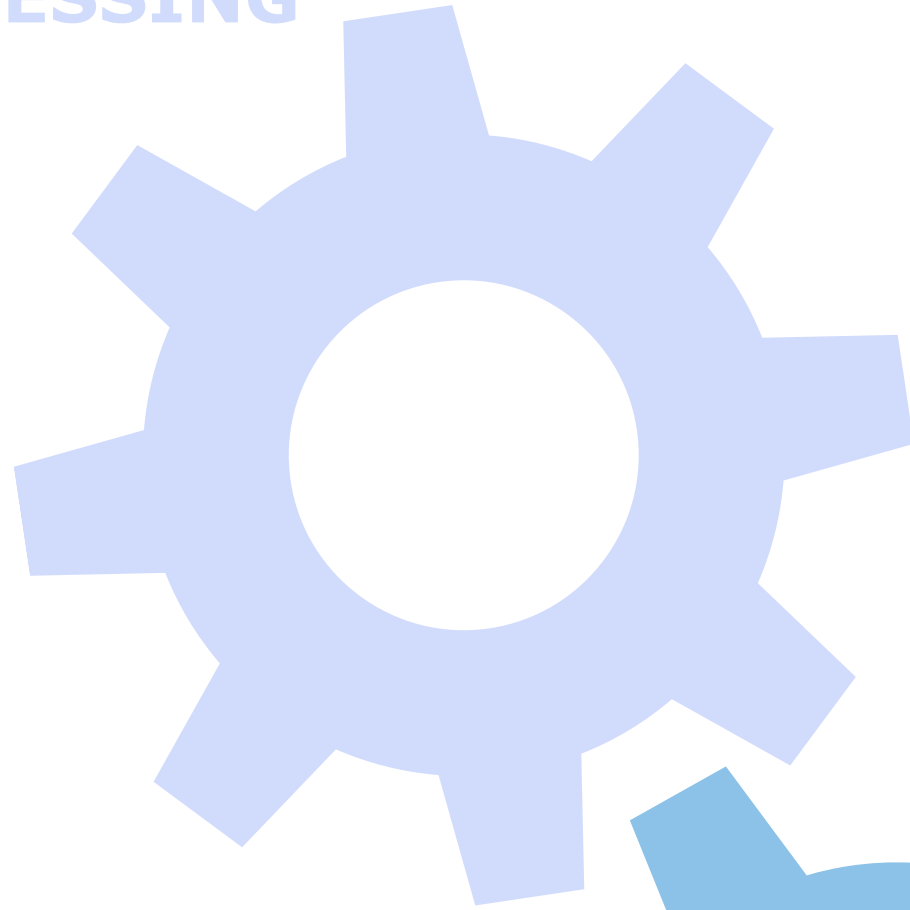
**REGION OF
INTEREST
IDENTIFICATION**



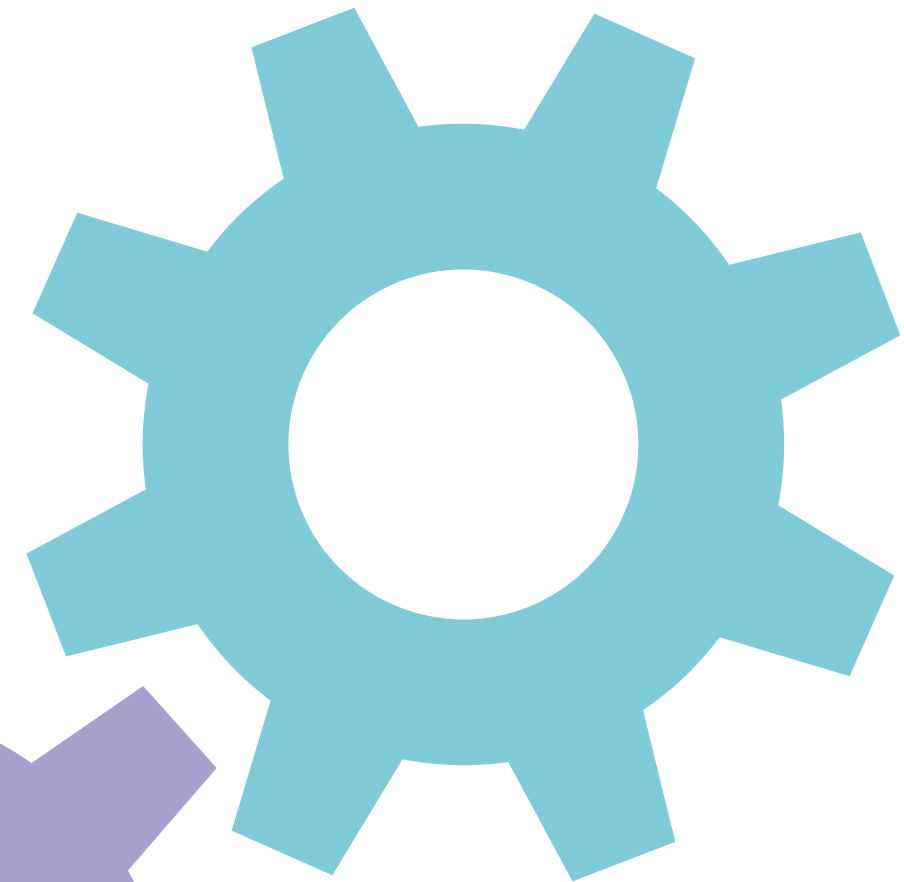
**MONTE CARLO
SIMULATIONS**



**IMAGE
PROCESSING**

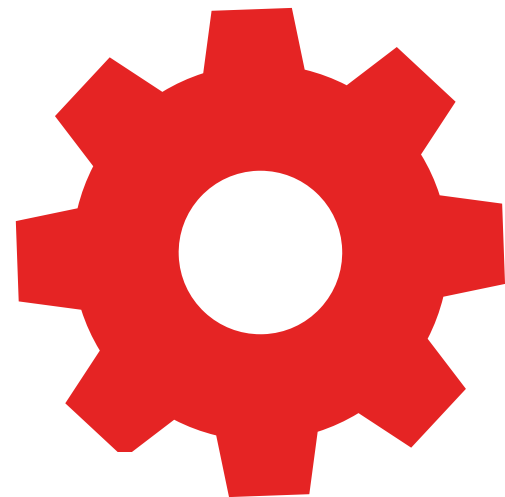


PATIENT MODELING

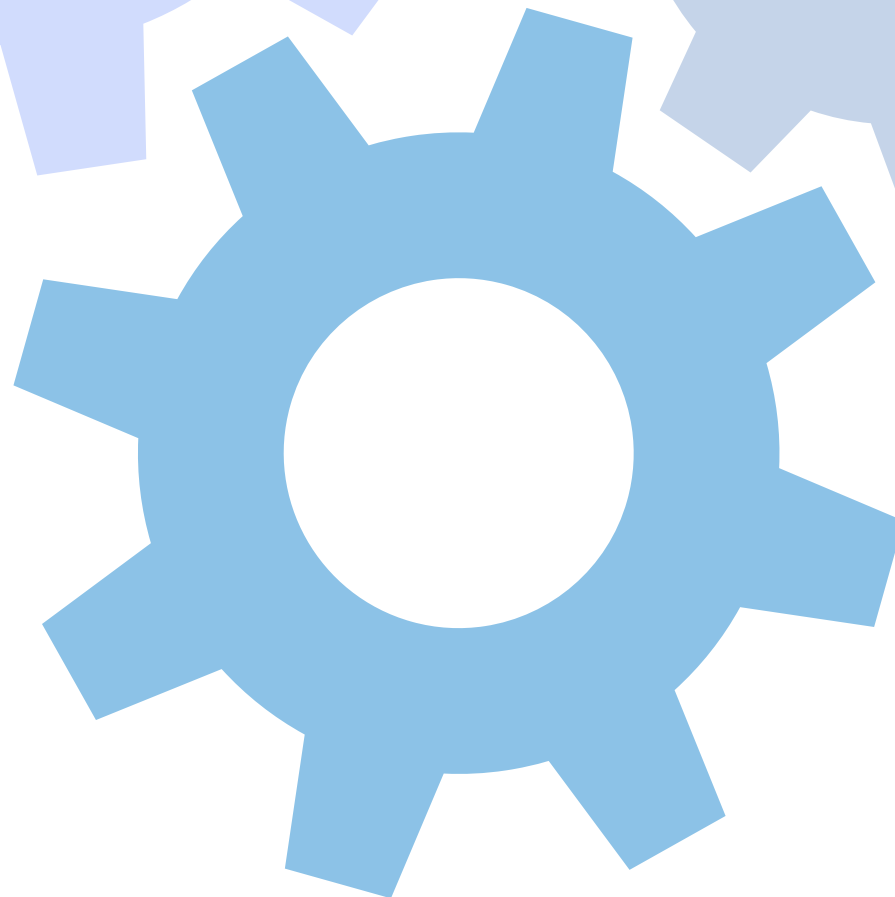


**DOSIMETRIC
ANALYSIS**

**AUTOMATIC
SEGMENTATION**



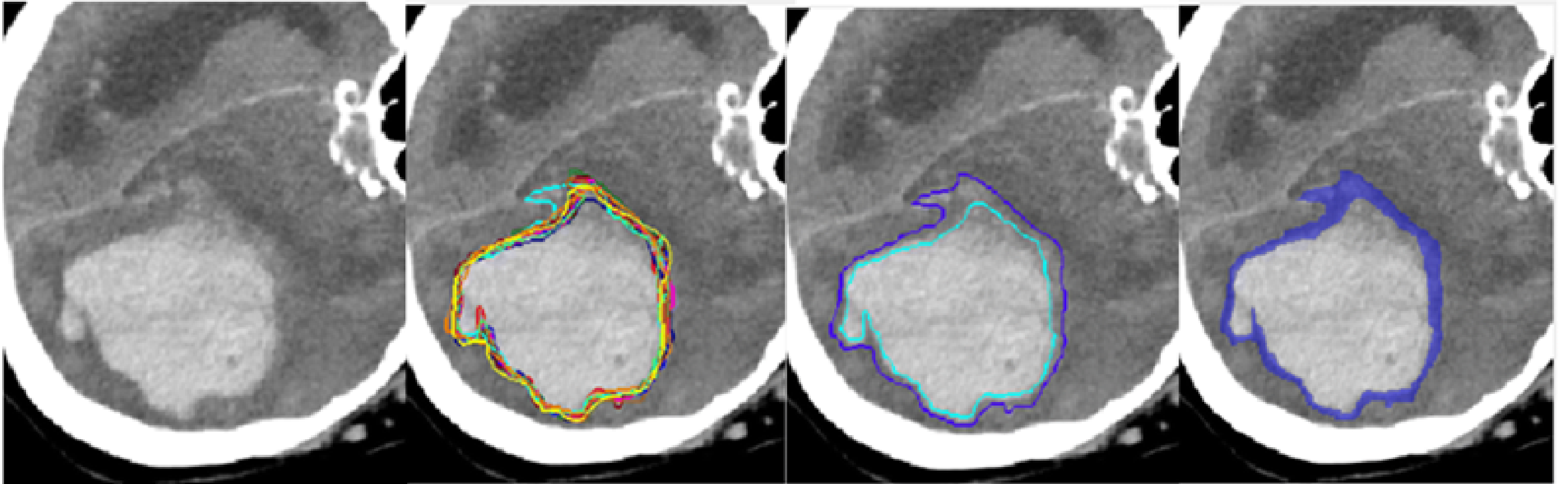
**REGION OF INTEREST
IDENTIFICATION**



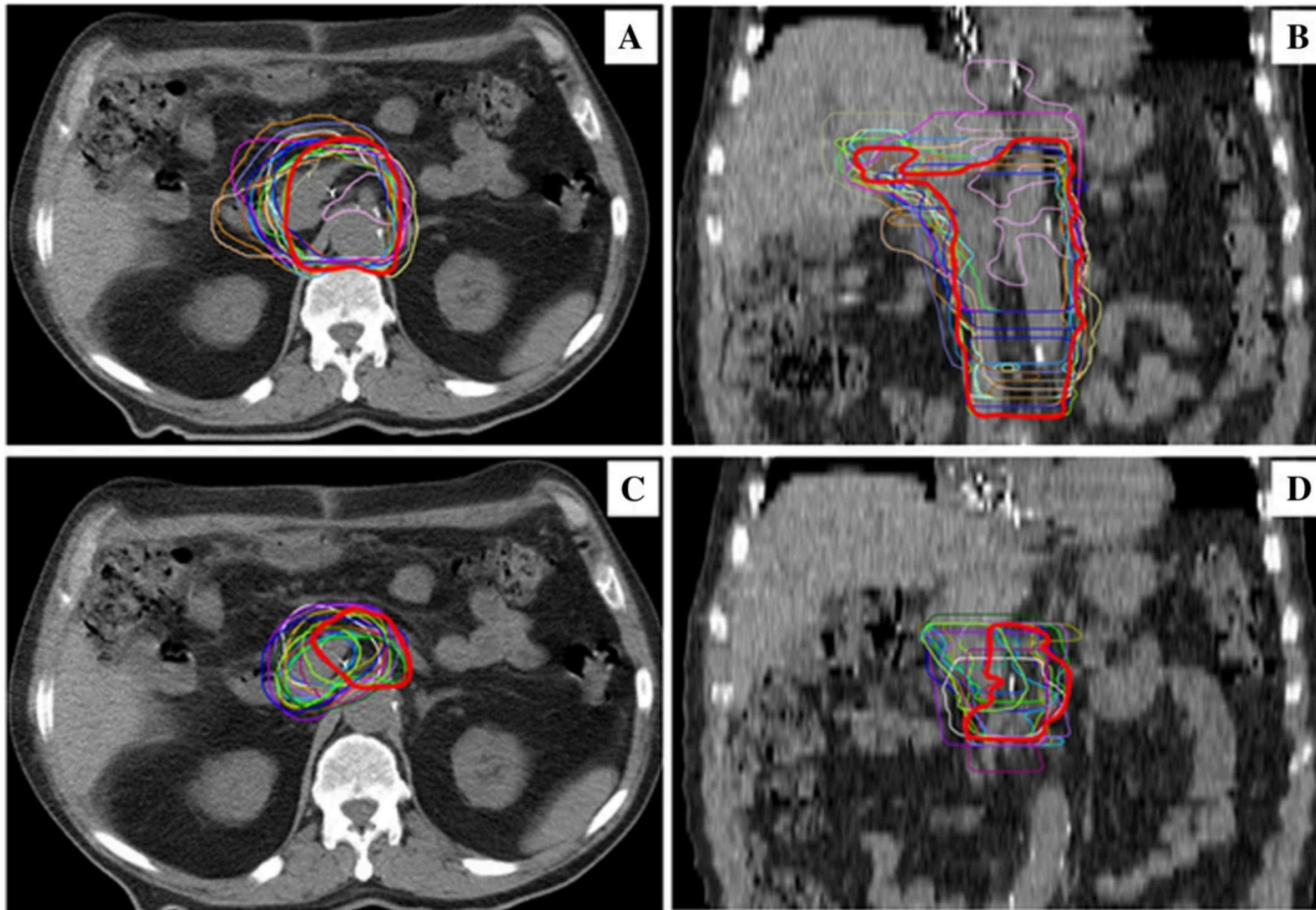
**MONTE CARLO
SIMULATIONS**



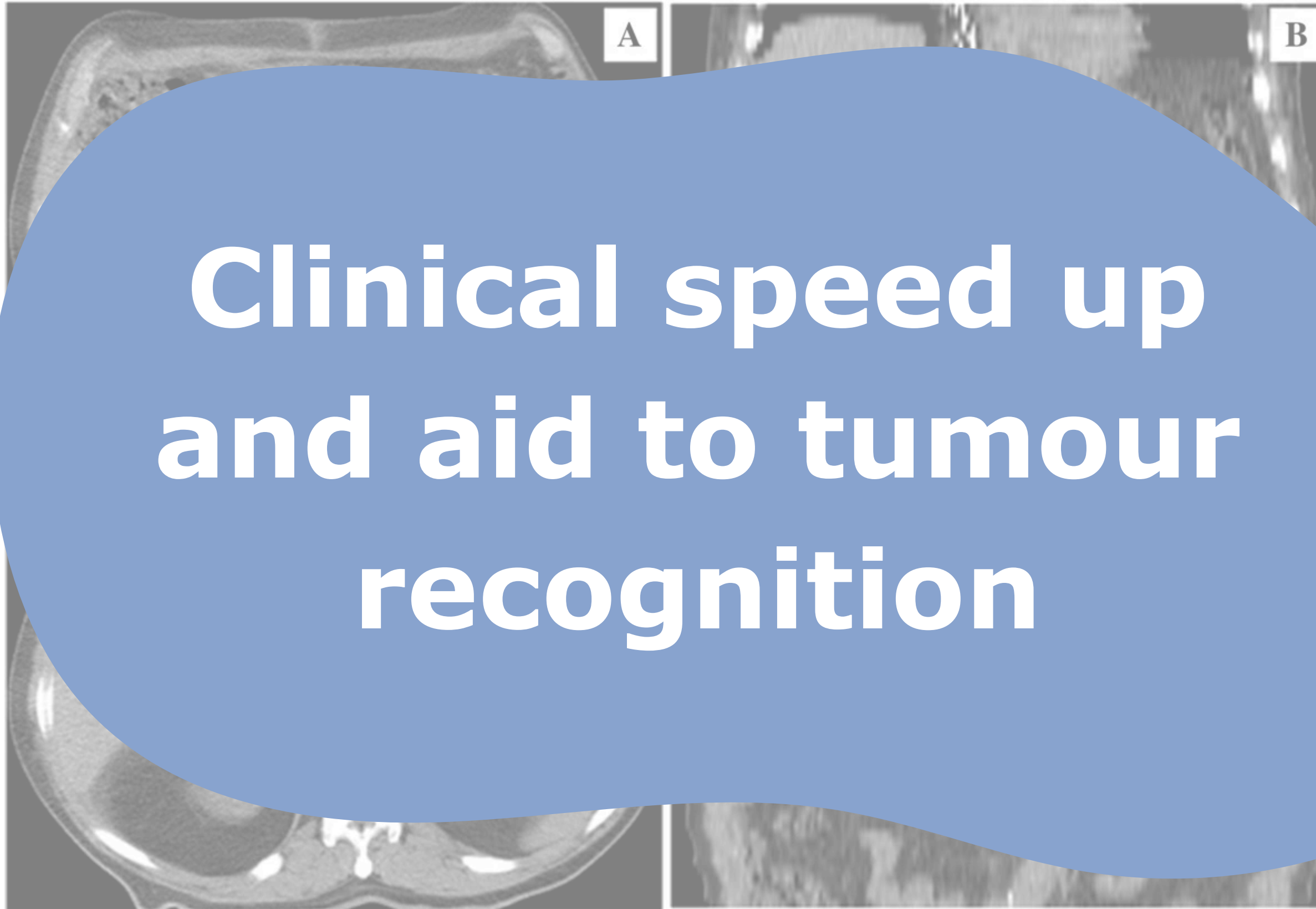
Manual Contouring



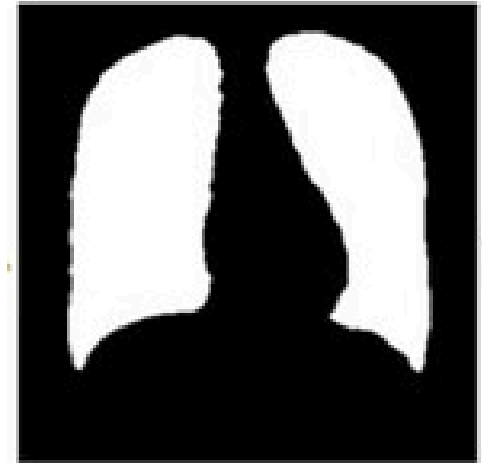
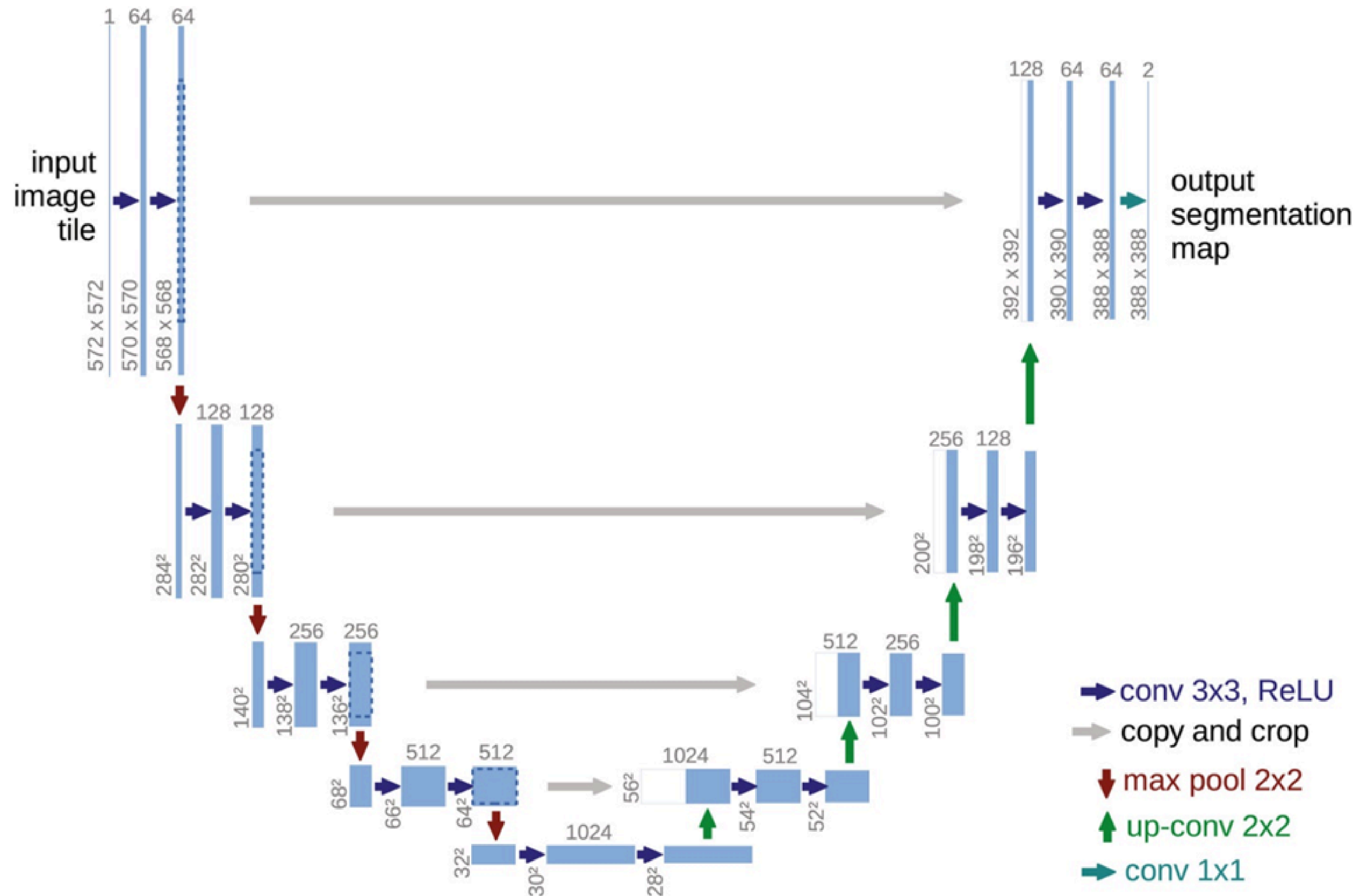
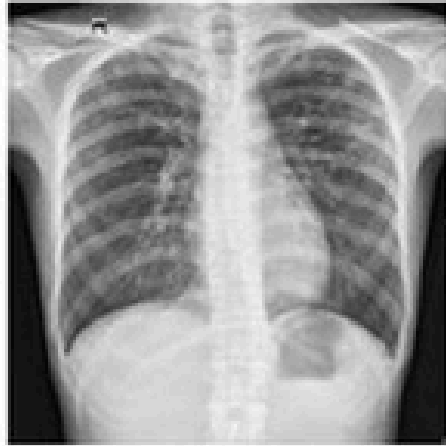
Manual Contouring



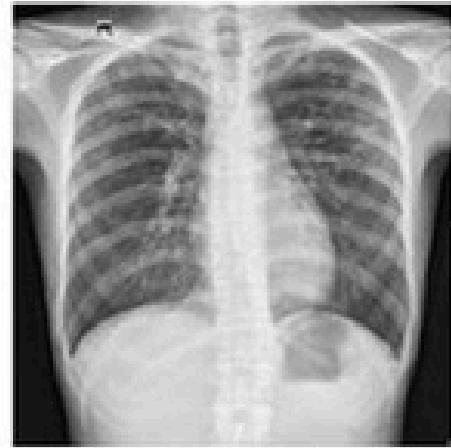
Automatic Segmentation



nnU-Net

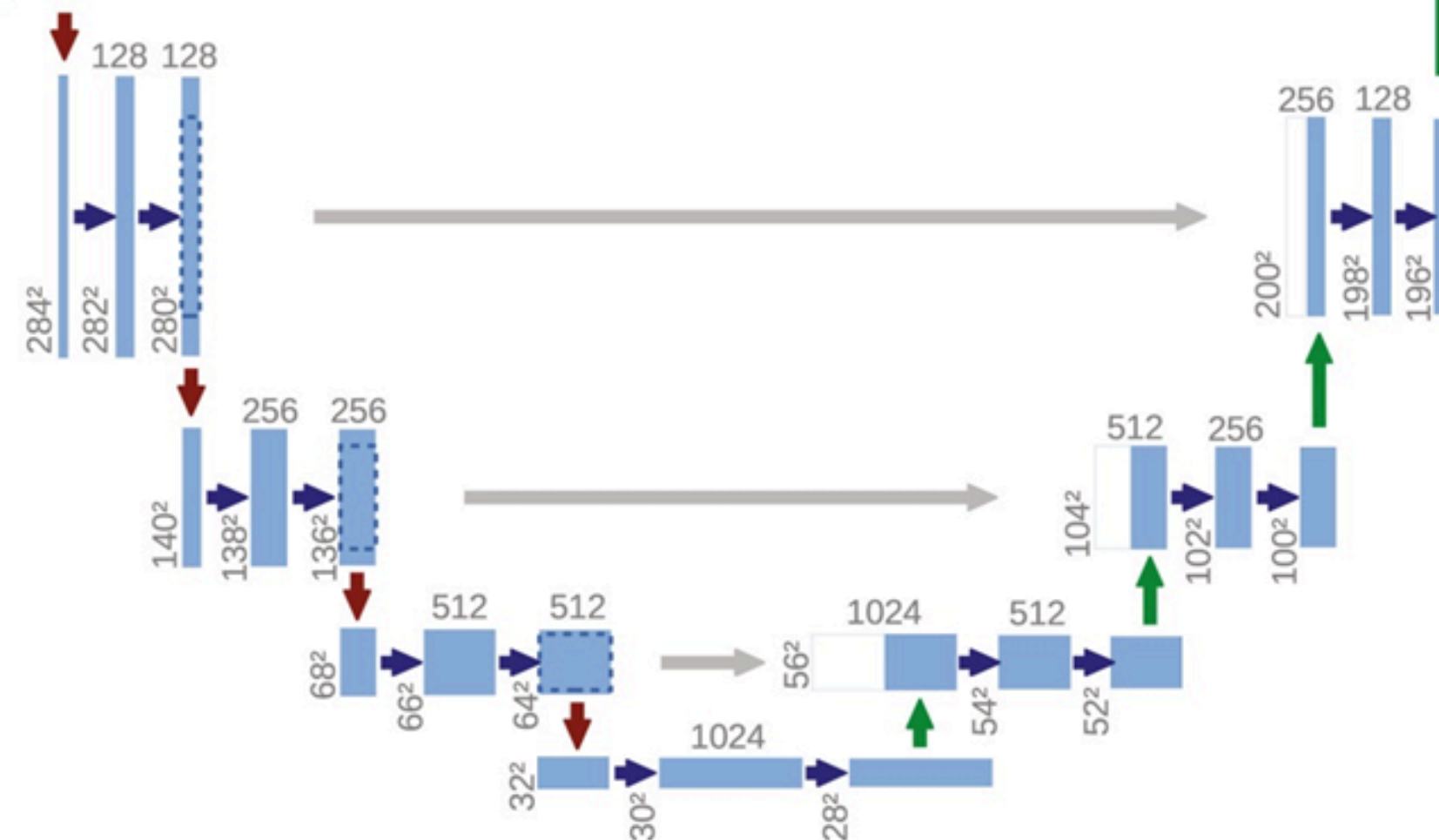


nnU-Net



Contracting Path (encoder) feature extraction

Expansive Path (decoder) spatially locates the features and generates an output map



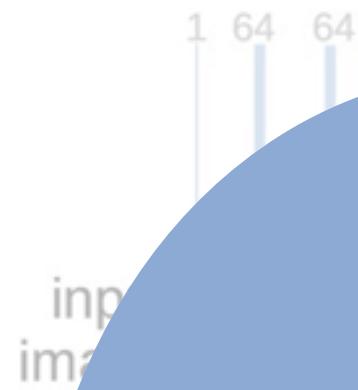
- conv 3x3, ReLU
- copy and crop
- ↓ max pool 2x2
- ↑ up-conv 2x2
- conv 1x1



nnU-Net

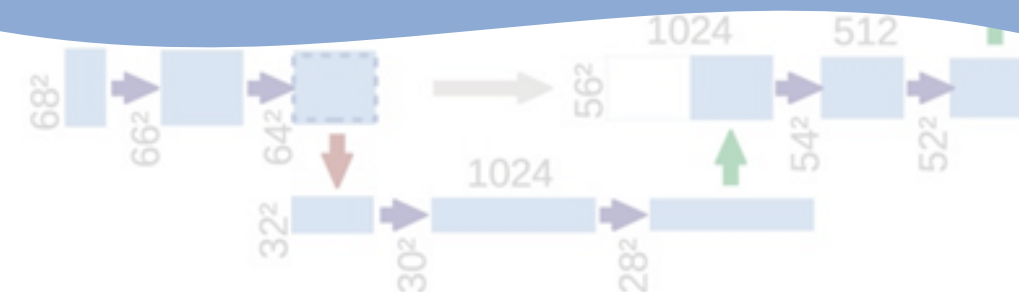


Contracting Path (encoder) feature extraction



(decoder) generates an ap

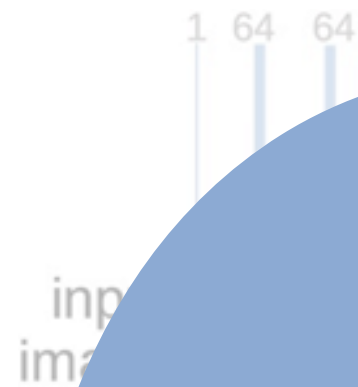
Test the neural network effectiveness



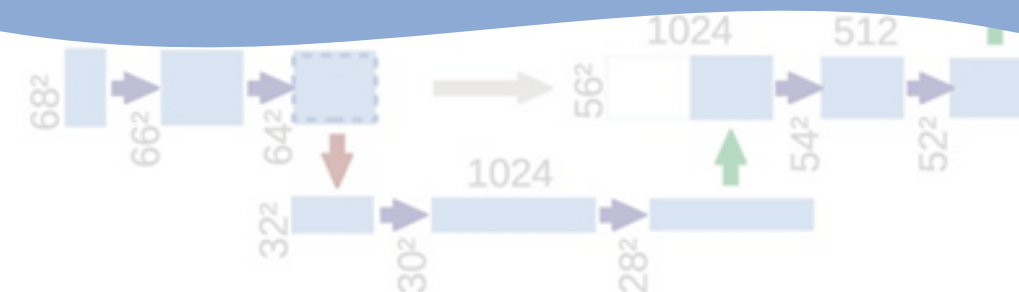
nnU-Net



Contracting Path (encoder) feature extraction



(decoder) generates an ap



↑ up-conv 2x2
→ conv 1x1



DATASET CREATION

TRAIN SET

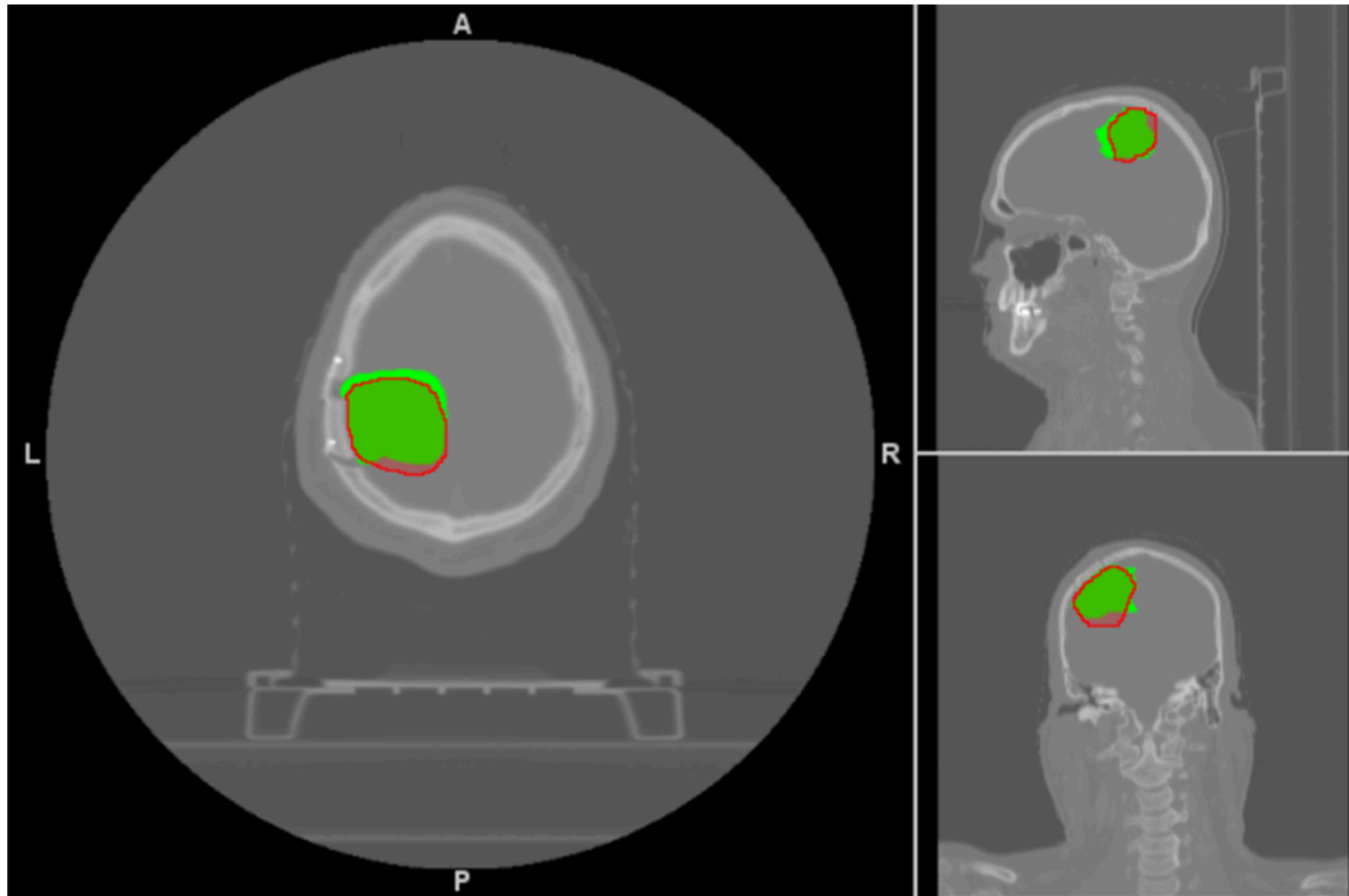
TEST SET

152 (76.7%)

46 (23.3%)

198 CT-images from *The Cancer Imaging Archive*

www.cancerimagingarchive.net

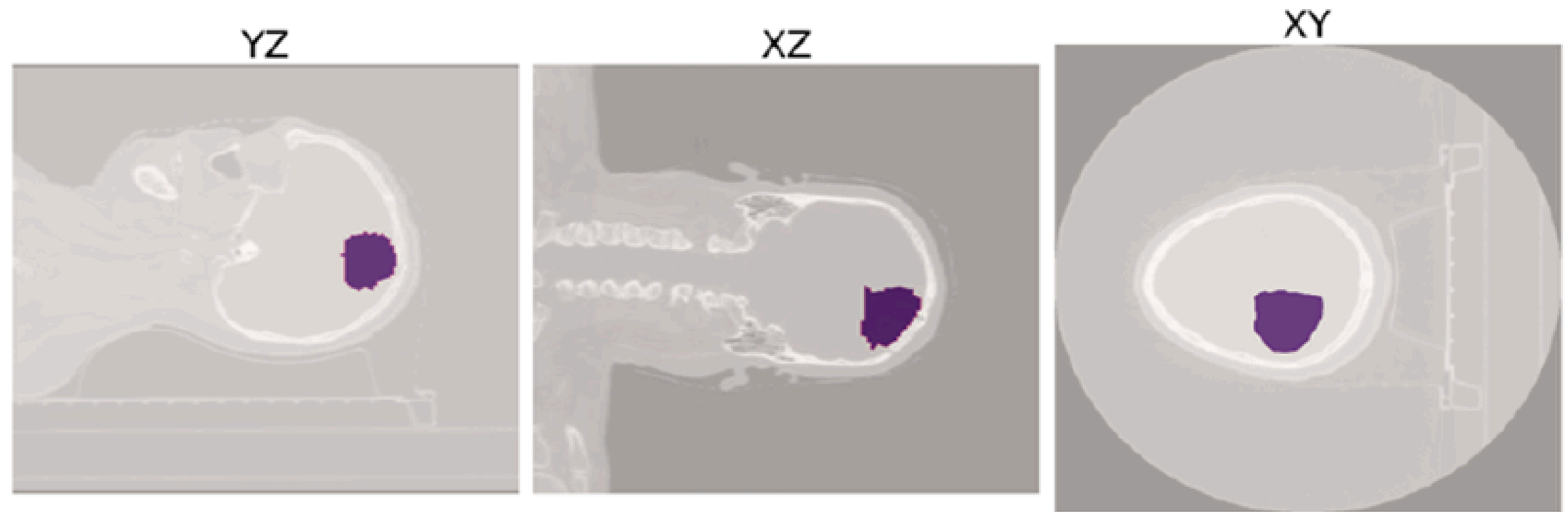


DICE = 0.824

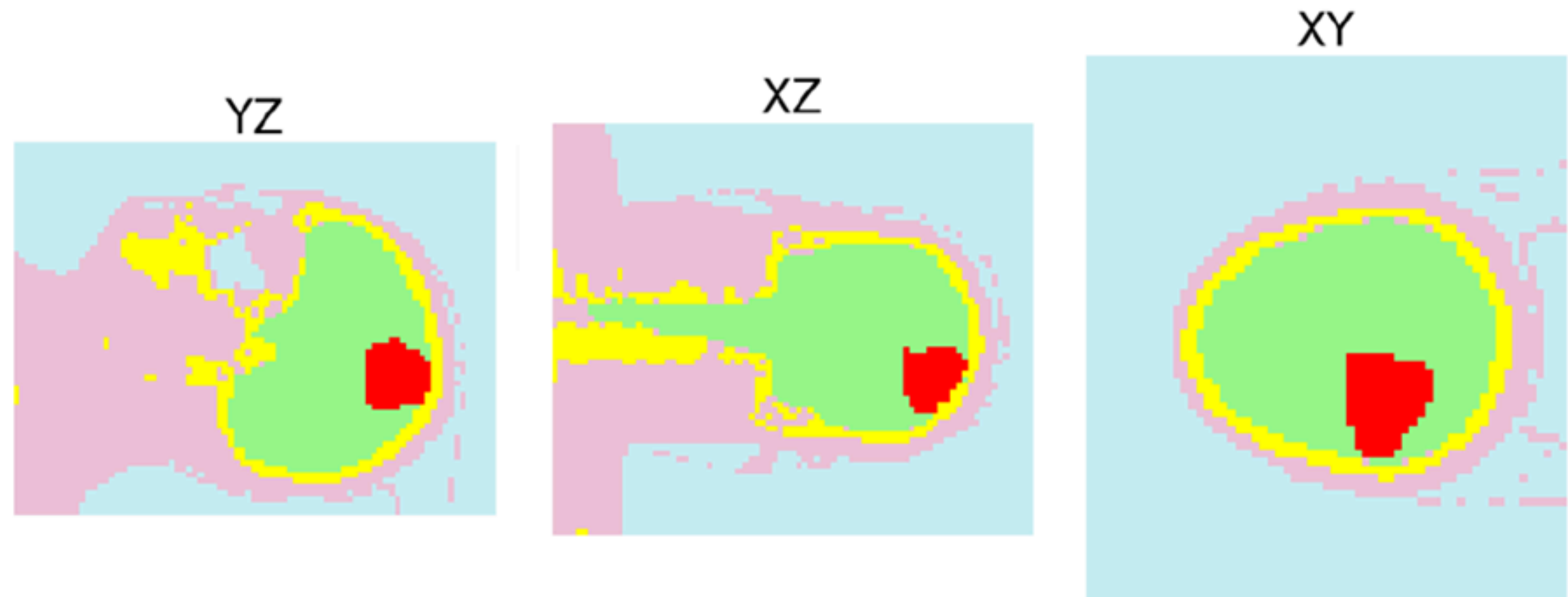
**True Tumour
Volume**

**Predicted Tumour
Volume**

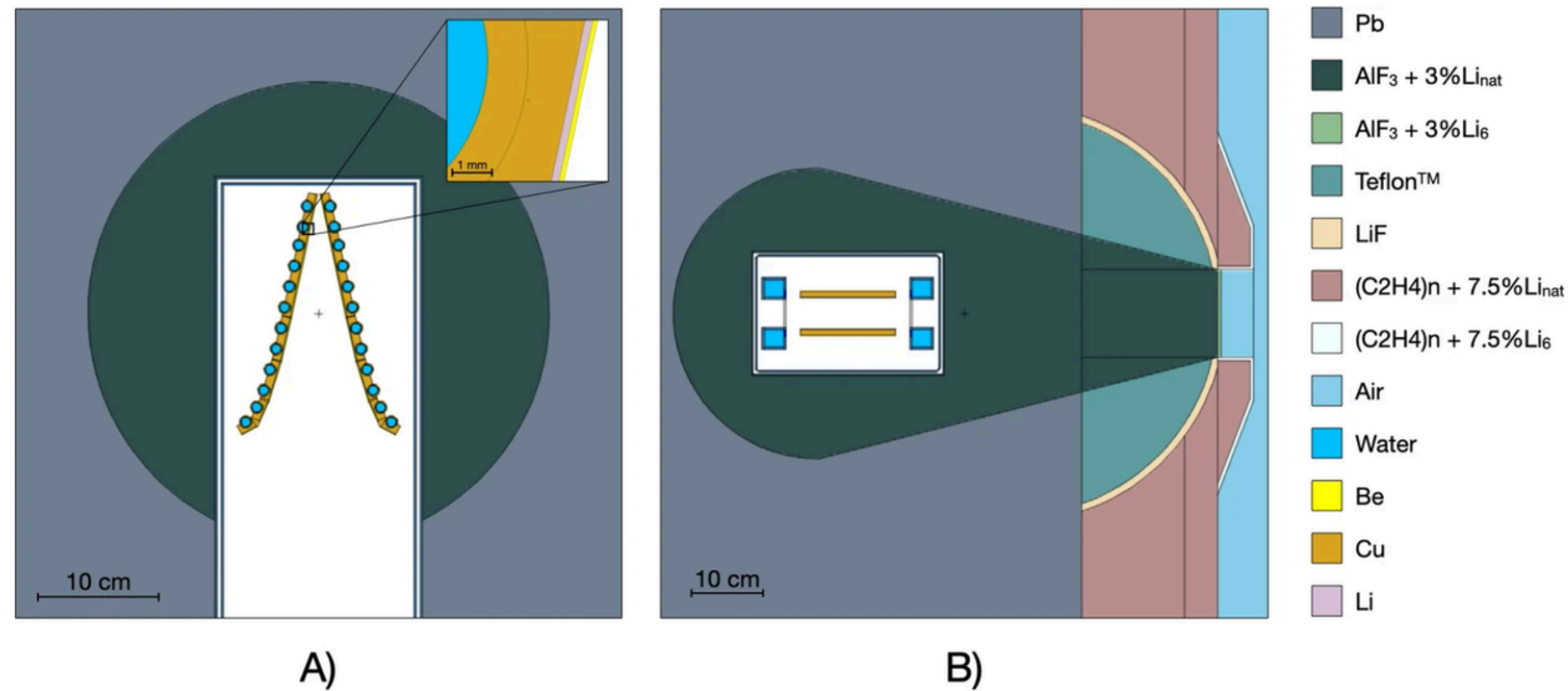
CT + GTV



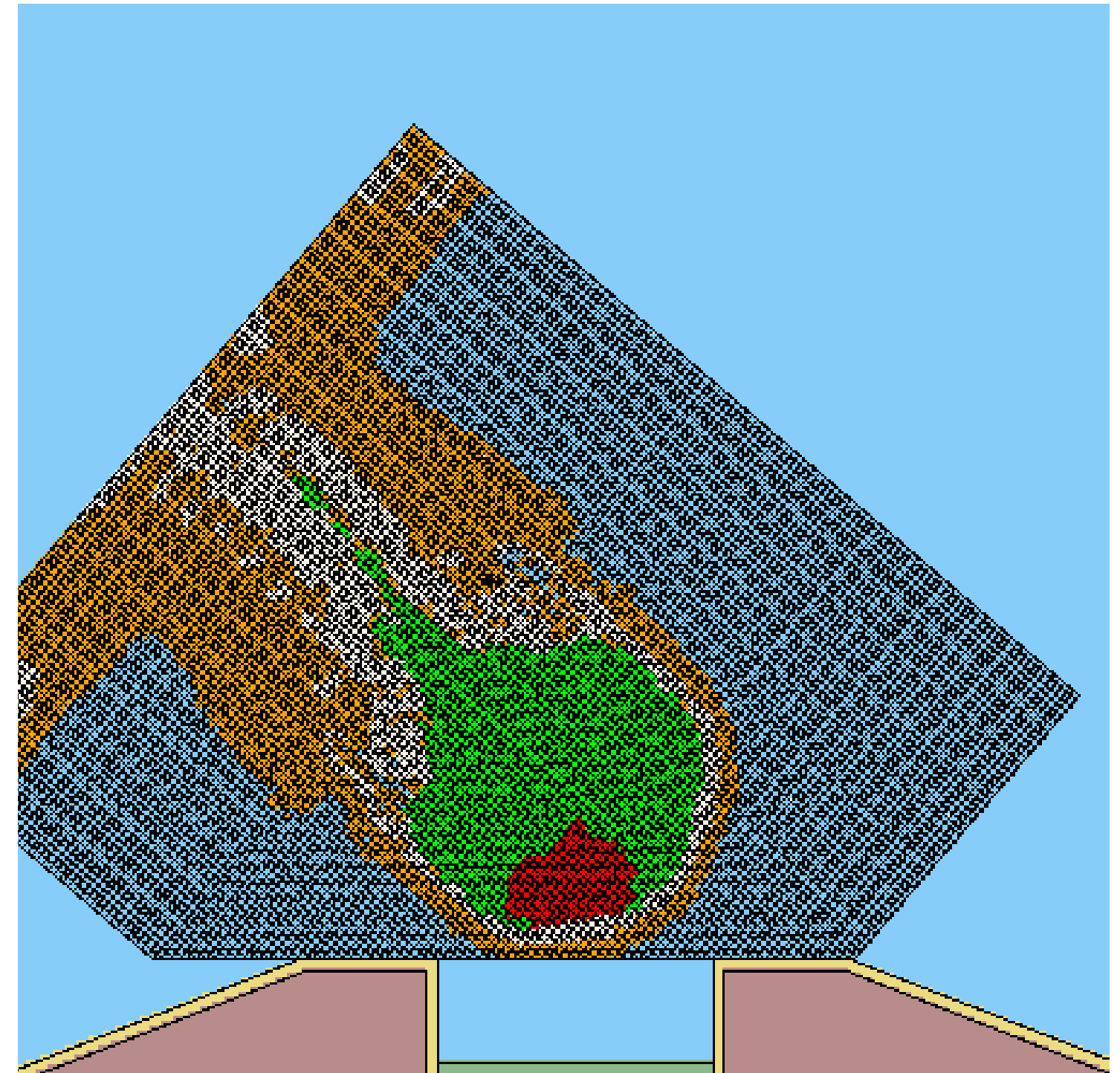
**Voxelised
image**



TREATMENT SETUP



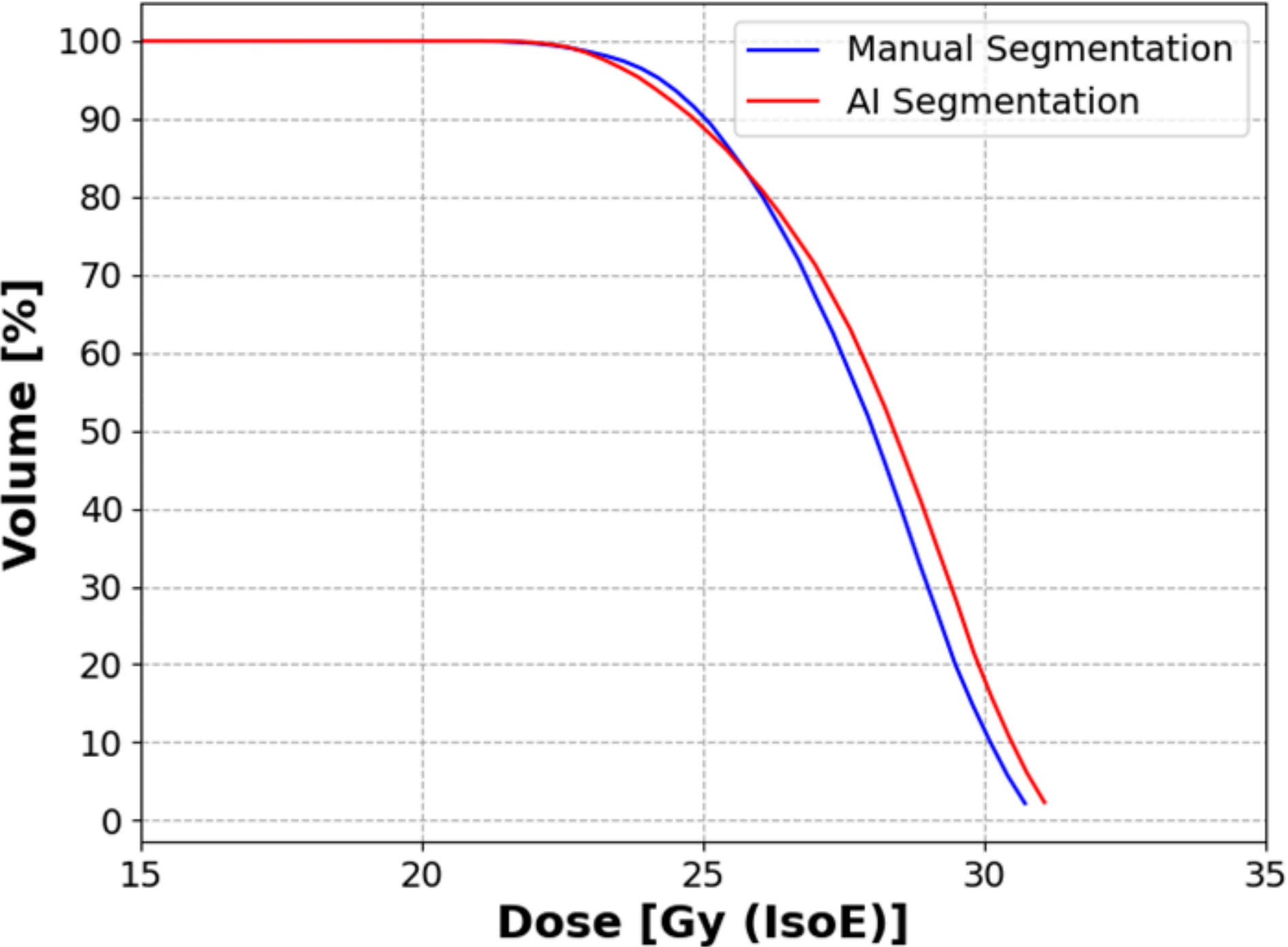
Postuma, I. et al. *A Novel Approach to Design and Evaluate BNCT Neutron Beams Combining Physical, Radiobiological, and Dosimetric Figures of Merit.* Biology 2021, 10, 174.



DOSIMETRIC COMPARISON

Photon Isoeffective Dose Model

C. Pezzi, et al. *Dosimetric comparison of the BNCT treatment planning performances when using a nnU-NET to automatically segment GBM*, Health Technol. 15, 811–822 (2025).
<https://doi.org/10.1007/s12553-025-00996-2>

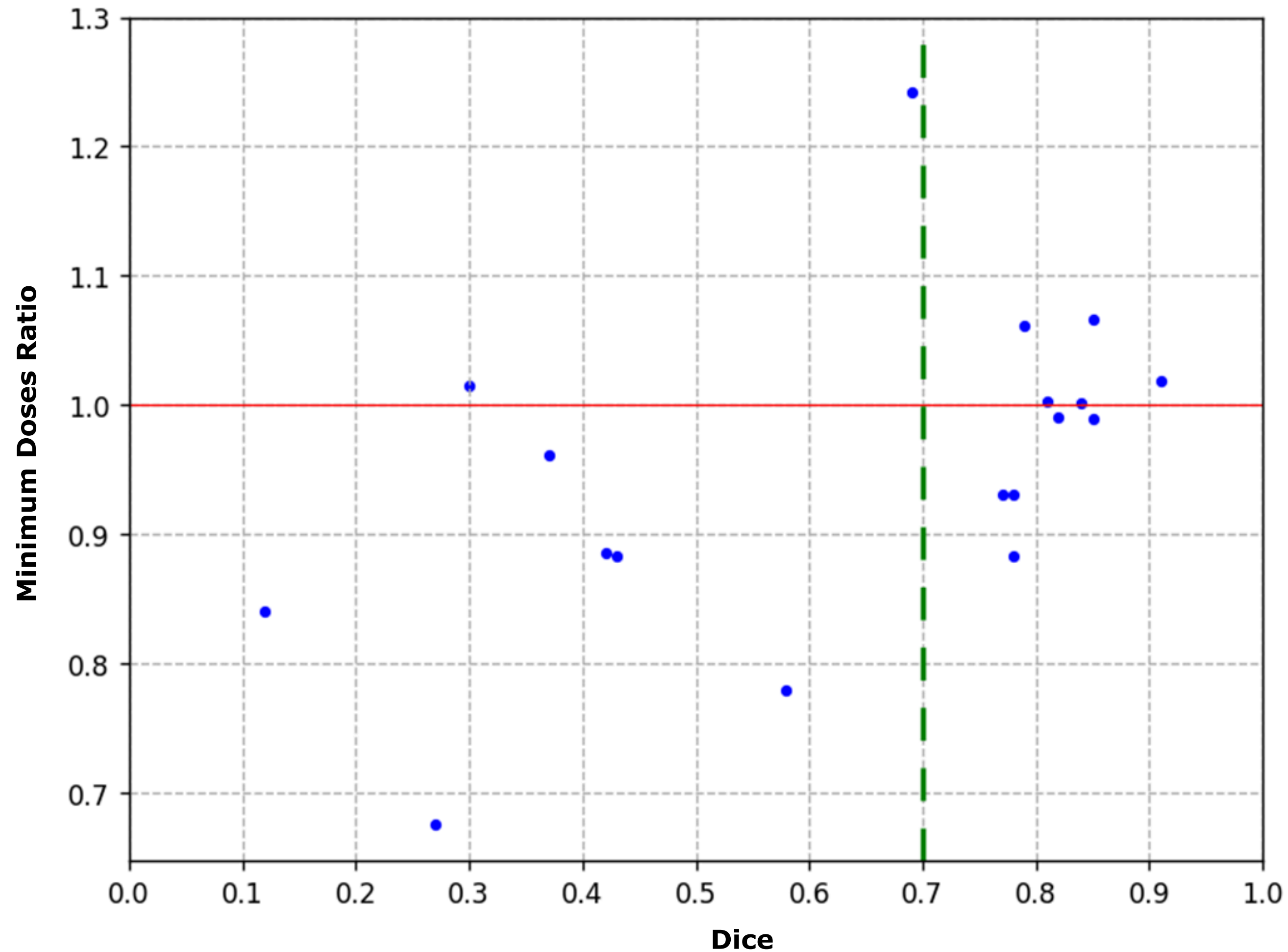


	GTV True	GTV NN
D98% [Gy (IsoE)]	23.3	23.1
D50% [Gy (IsoE)]	28.0	28.4
D2% [Gy (IsoE)]	30.7	31.1

Variation [%]
0.9
1.4
1.3

DOSIMETRIC COMPARISON

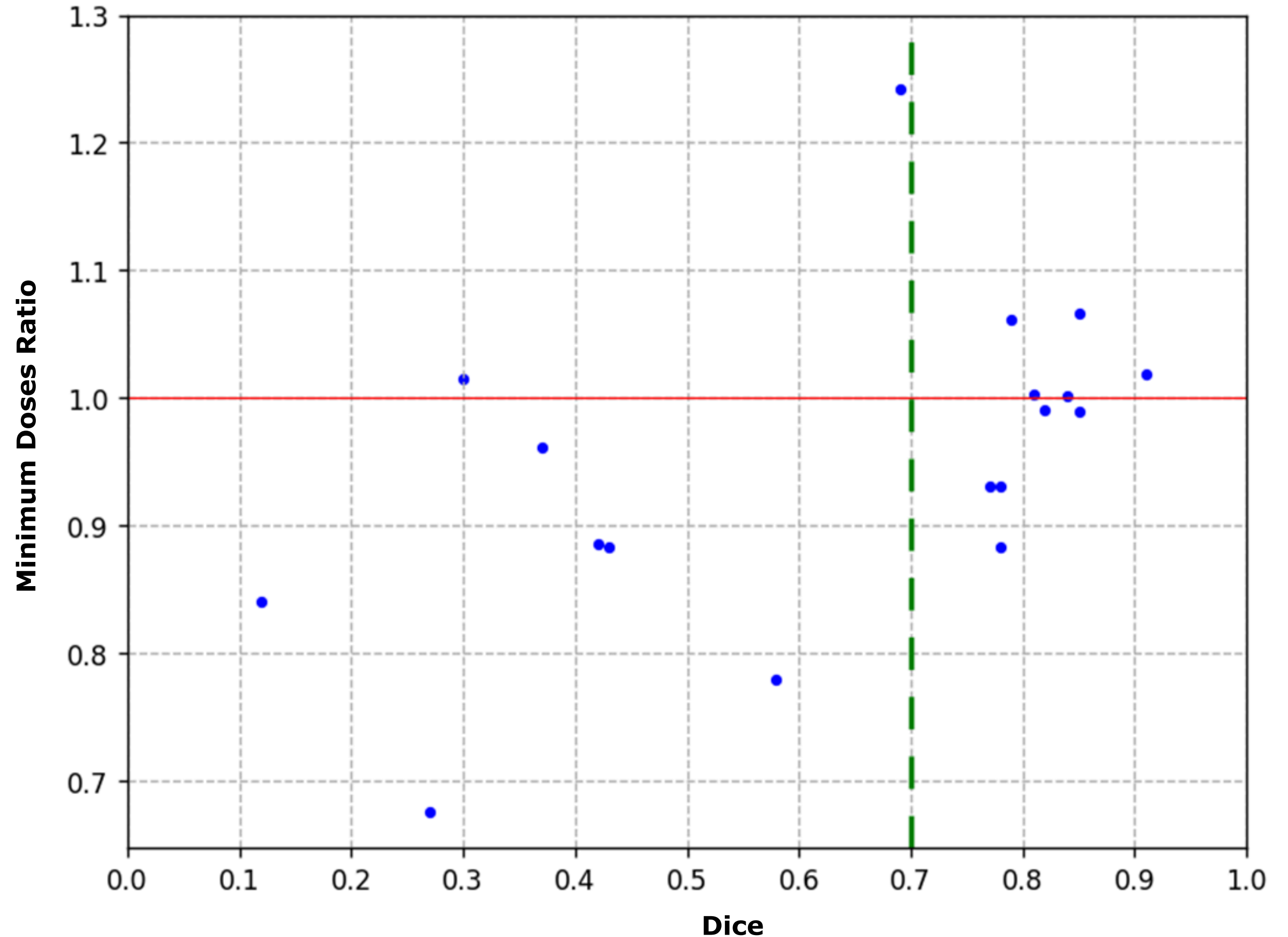
C. Pezzi, et al. *Dosimetric comparison of the BNCT treatment planning performances when using a nnU-NET to automatically segment GBM*, Health Technol. 15, 811–822 (2025).
<https://doi.org/10.1007/s12553-025-00996-2>



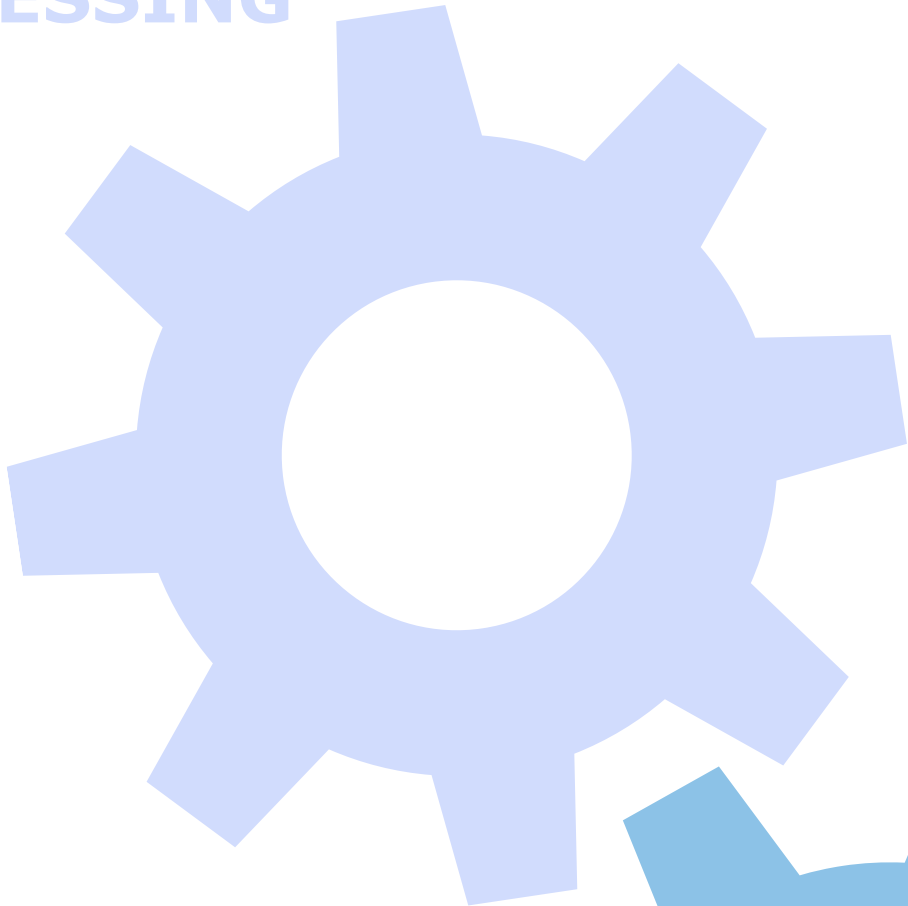
DOSIMETRIC COMPARISON

**Good performance
and similar dose
distributions**

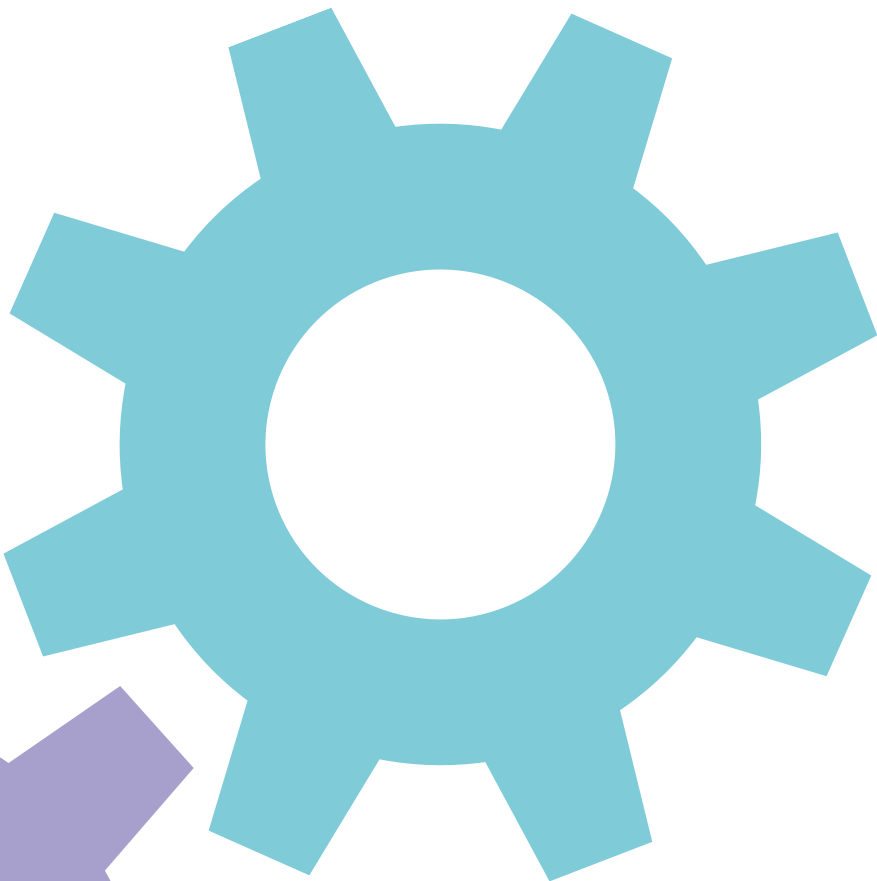
C. Pezzi, et al. *Dosimetric comparison
of the BNCT treatment planning
performances when
using a nnU-NET to automatically
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811–822 (2025).
<https://doi.org/10.1007/s12553-025-00996-2>



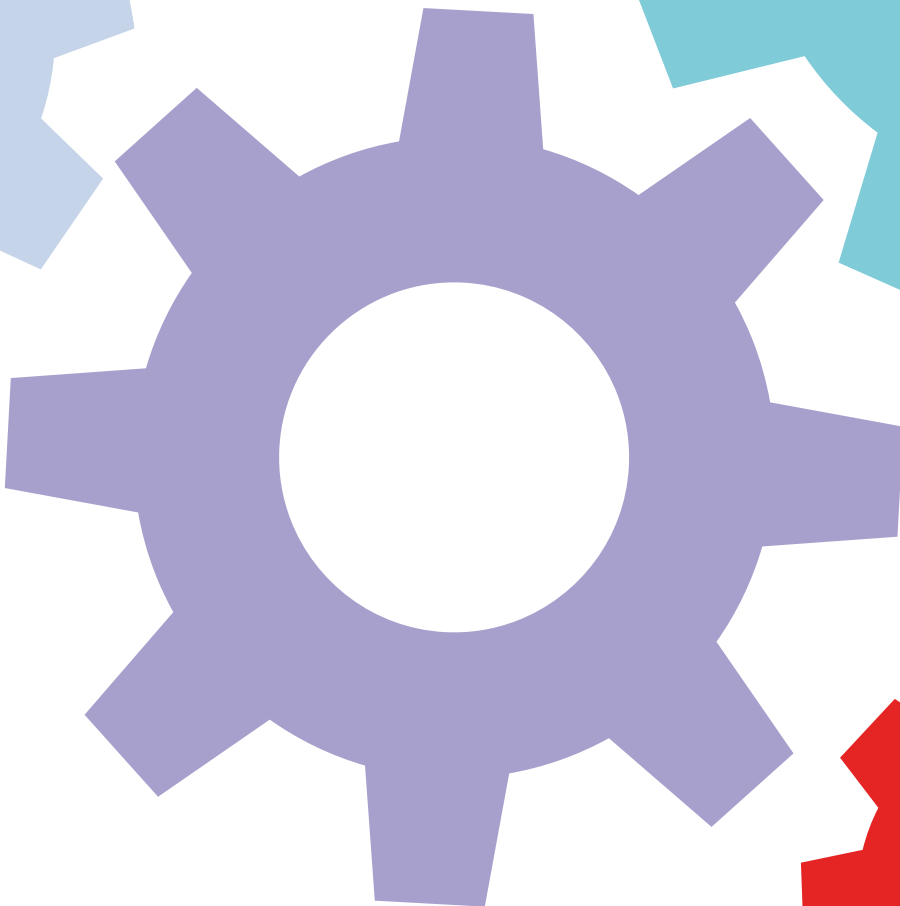
**IMAGE
PROCESSING**



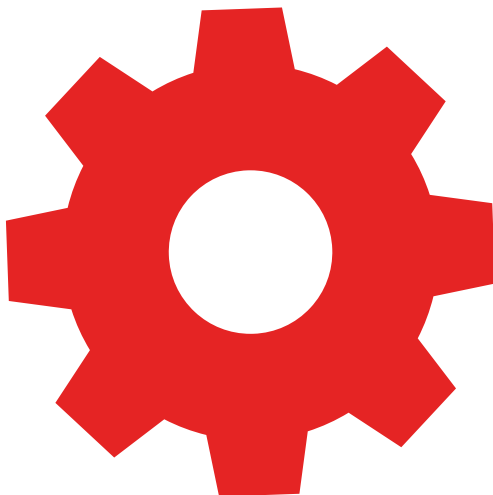
PATIENT MODELING



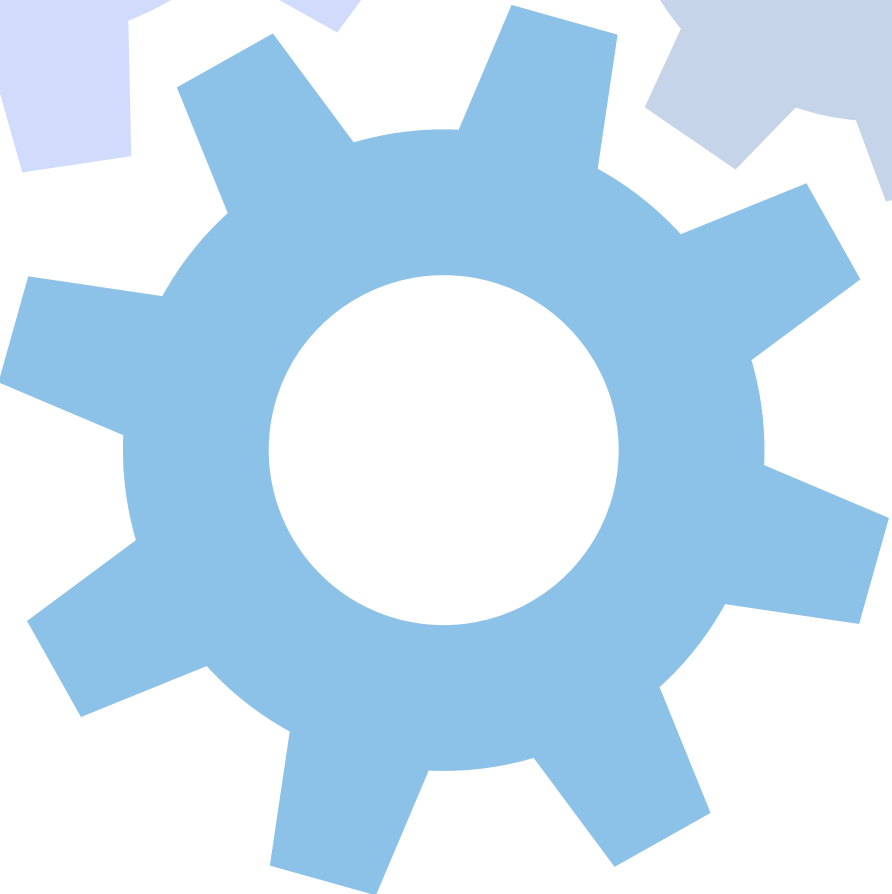
**DOSIMETRIC
ANALYSIS**



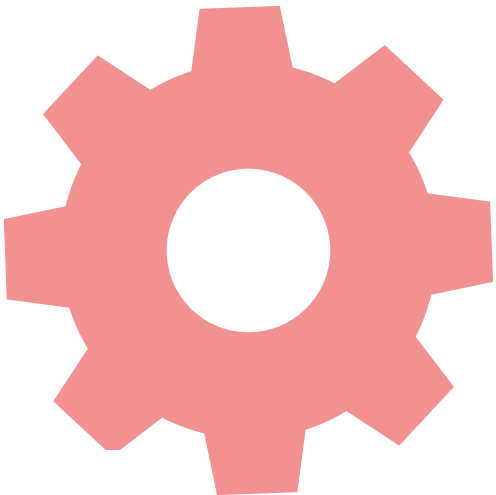
**MONTE CARLO
SIMULATIONS**



**AUTOMATIC
PATIENT
POSITIONING**

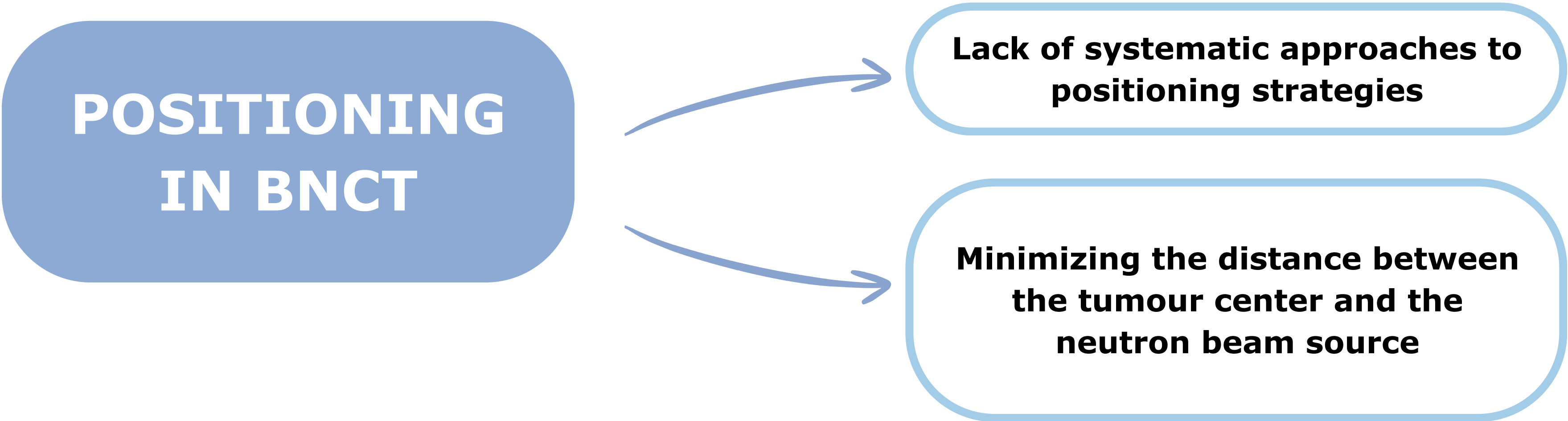


**REGION OF INTEREST
IDENTIFICATION**



**AUTOMATIC
SEGMENTATION**

POSITIONING IN BNCT



```
graph LR; A[POSITIONING IN BNCT] --> B[Lack of systematic approaches to positioning strategies]; A --> C[Minimizing the distance between the tumour center and the neutron beam source];
```

Lack of systematic approaches to positioning strategies

Minimizing the distance between the tumour center and the neutron beam source

I. Postuma, et al. *OpenPINT: Open-source Planning for Isoeffective Nuclear Treatments in BNCT*
research, arXiv, 2026,
<https://arxiv.org/pdf/2606.21476>

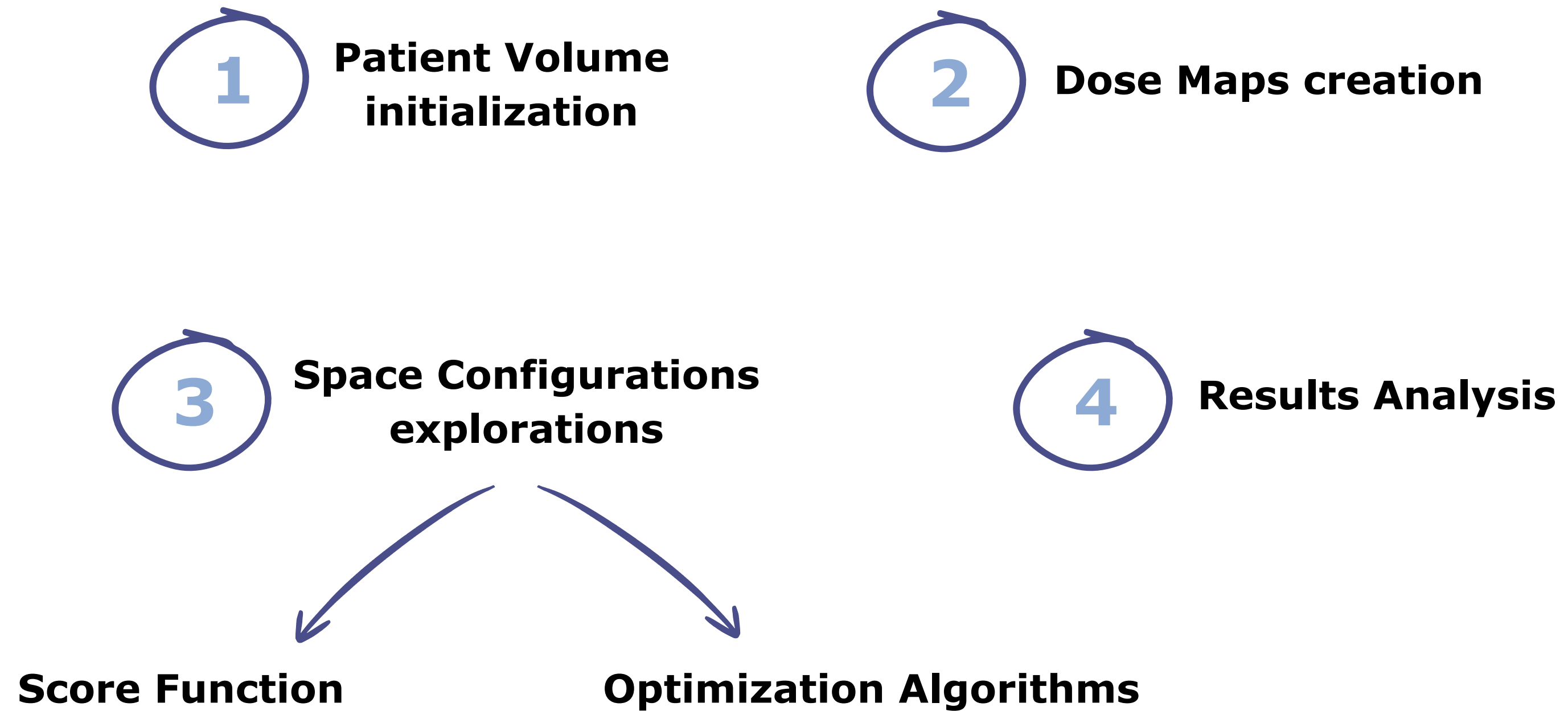
POSITIONING IN BNCT

**Lack of systematic approaches to
positioning strategies**

**Minimizing the distance between
the tumour center and the
neutron beam source**

IMPLEMENTATION OF A SEMI- AUTOMATIC PATIENT POSITIONING METHOD

POSITIONING IN BNCT



1

Patient Volume initialization

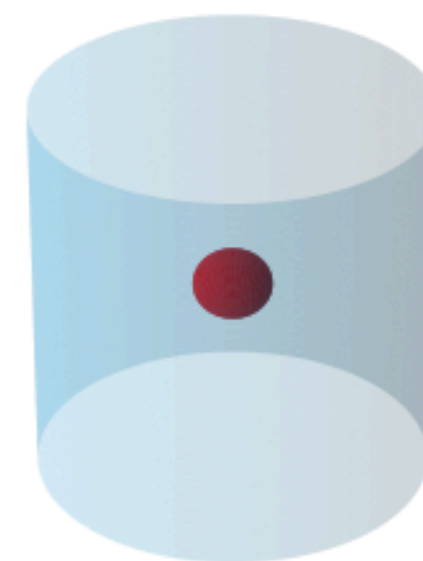
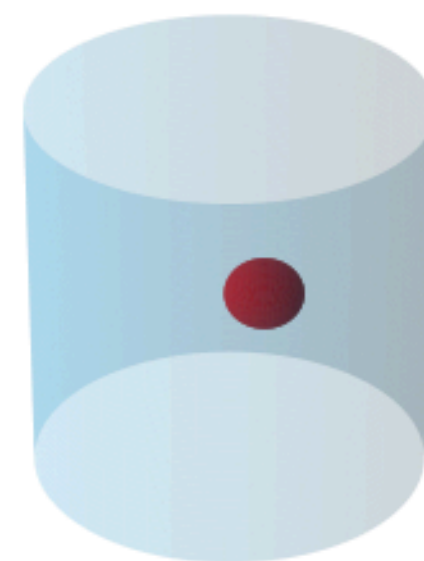
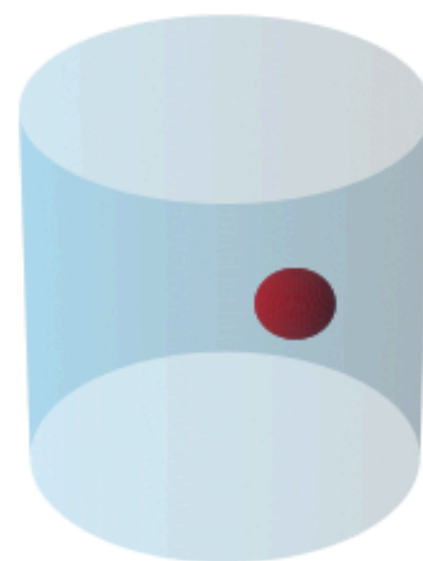
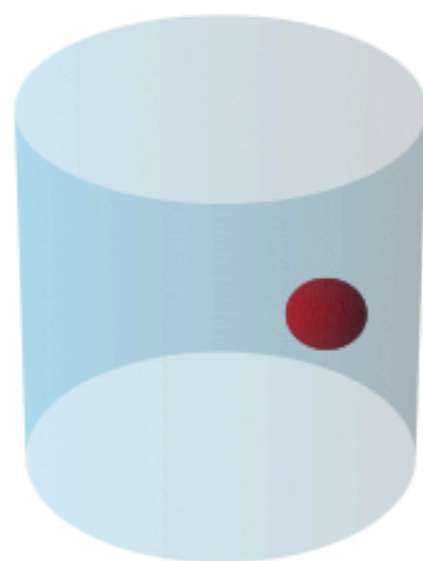
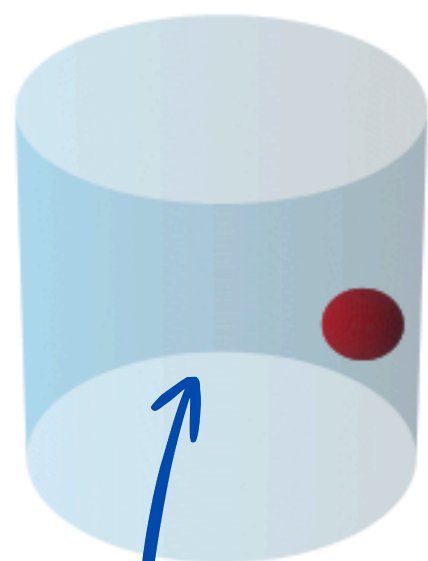
Distance = 0 mm

Distance = 20 mm

Distance = 40 mm

Distance = 60 mm

Distance = 80 mm

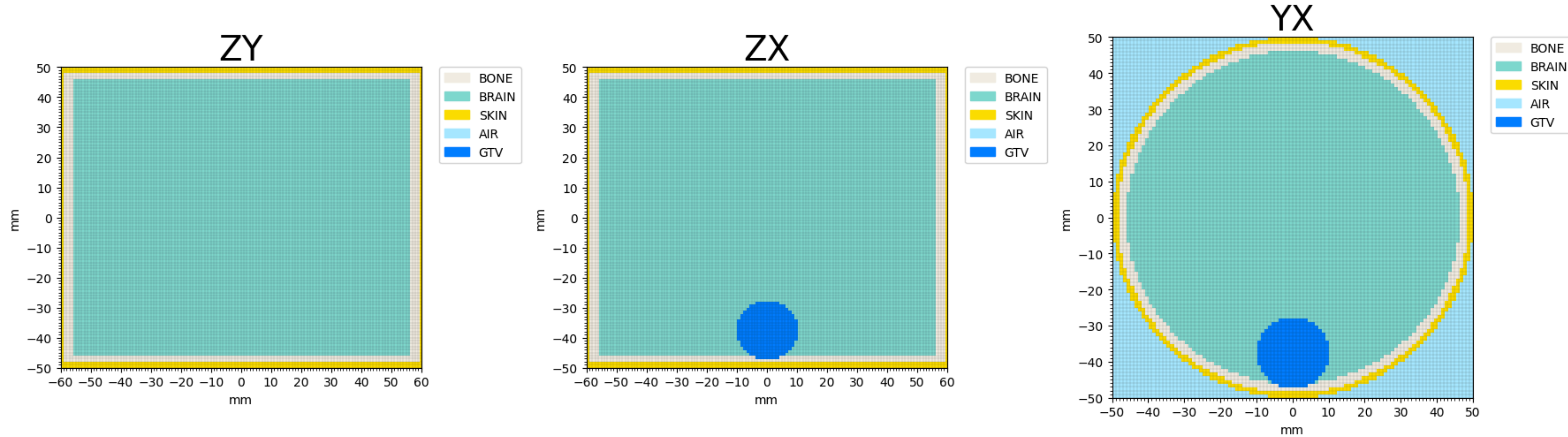


GTV

OAR

1

Patient Volume initialization



L. Provenzano, et al. *The essential role of radiobiological figures of merit for the assessment and comparison of beam performances in boron neutron capture therapy*, Physica Medica, Volume 67, 2019

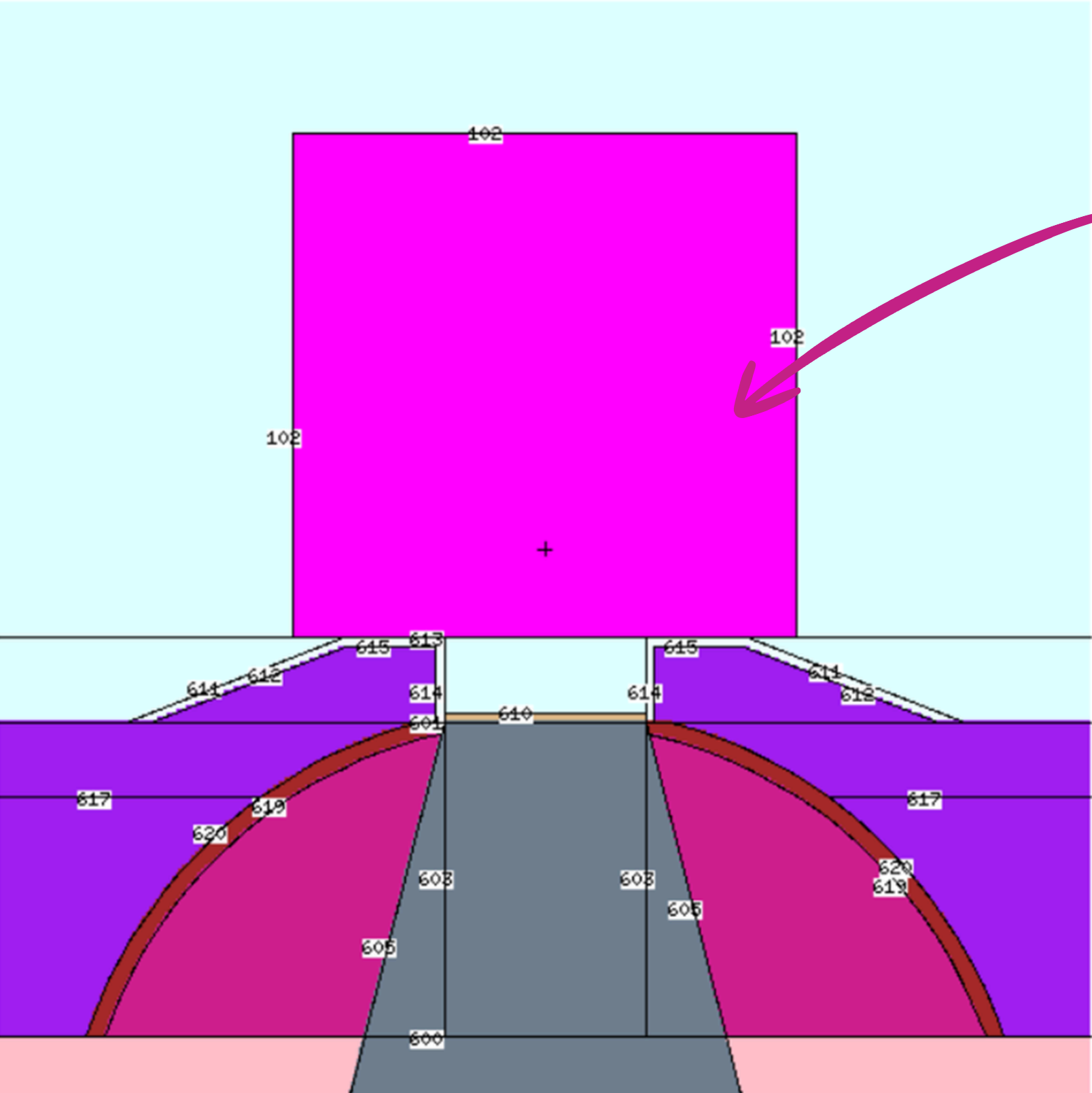
Cylinder Radius = 10 cm
Cylinder Height = 24 cm
Skull Thickness = 5 mm
Skin Thickness = 3 mm

Voxel size = 2 mm

Sphere Radius = 2 cm

2

Dose Maps creation

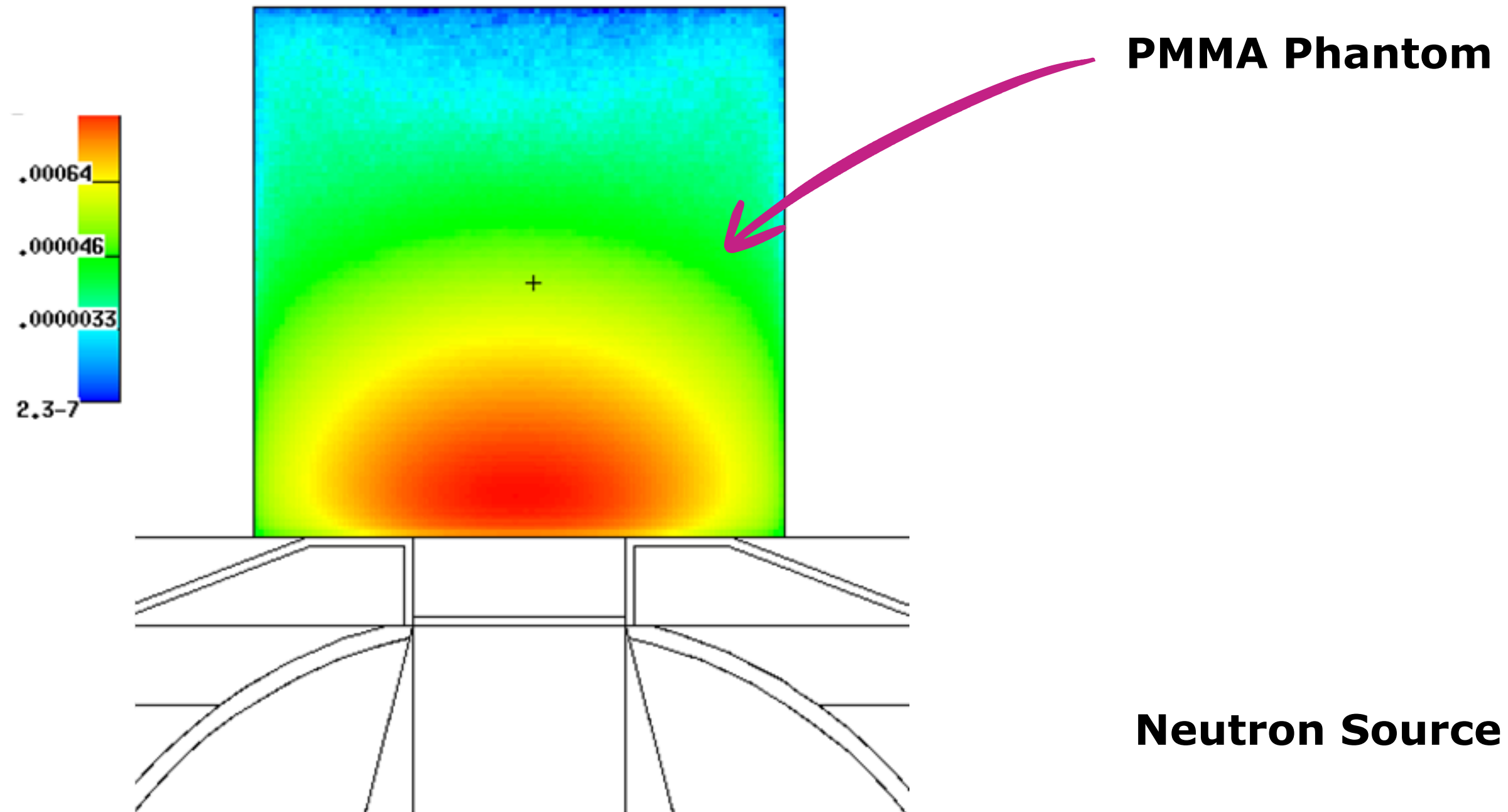


PMMA Phantom

Neutron Source

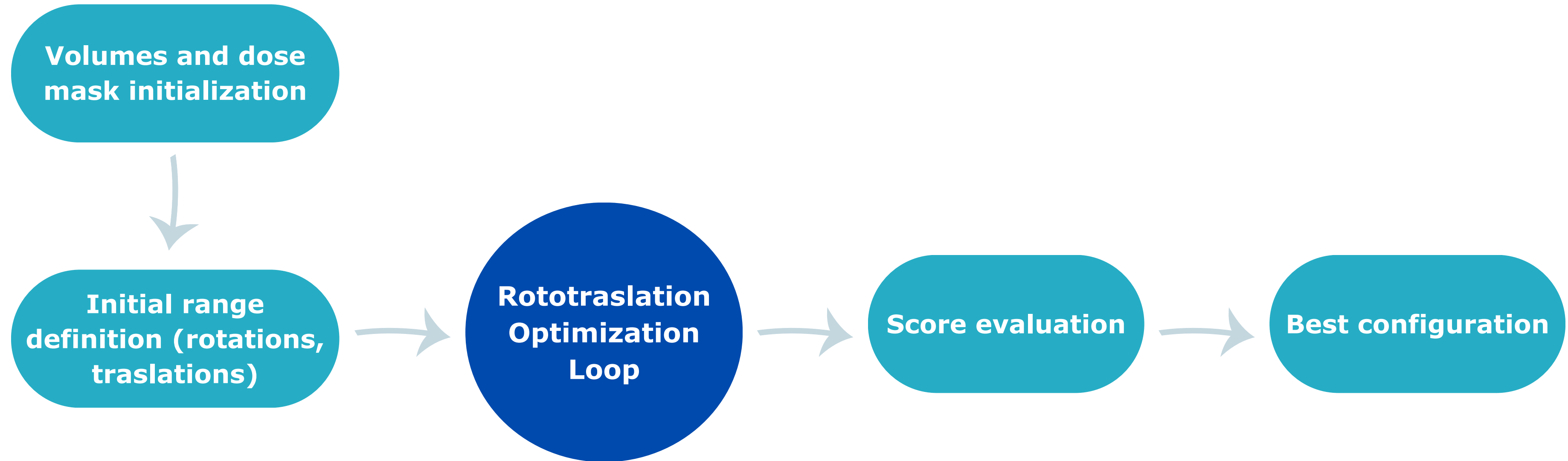
2

Dose Maps creation



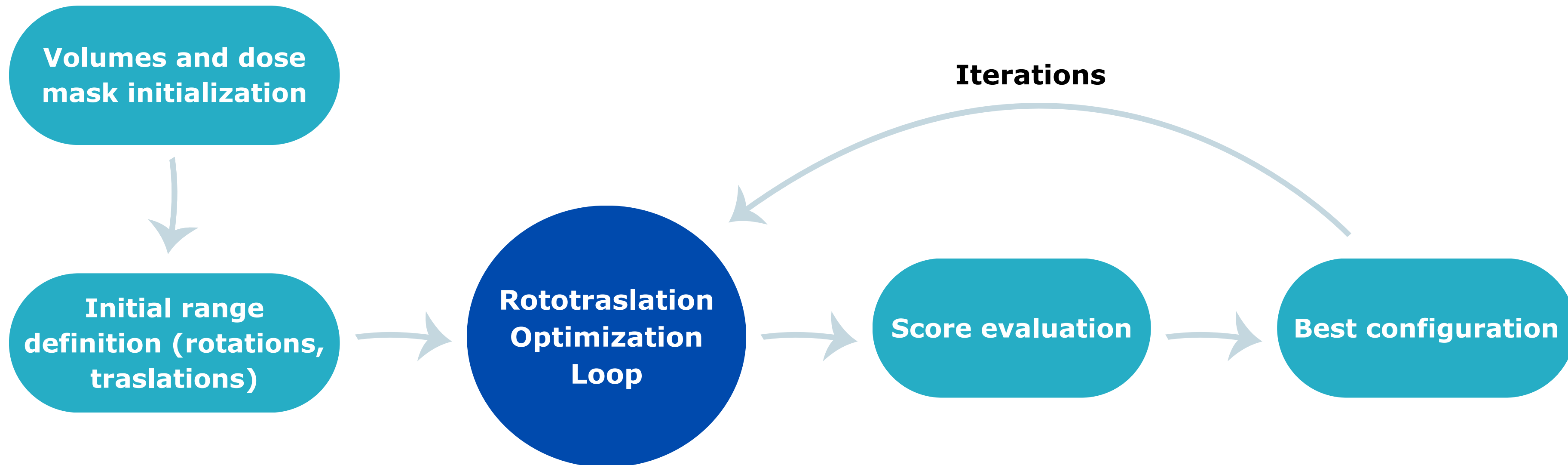
3

Space Configurations explorations



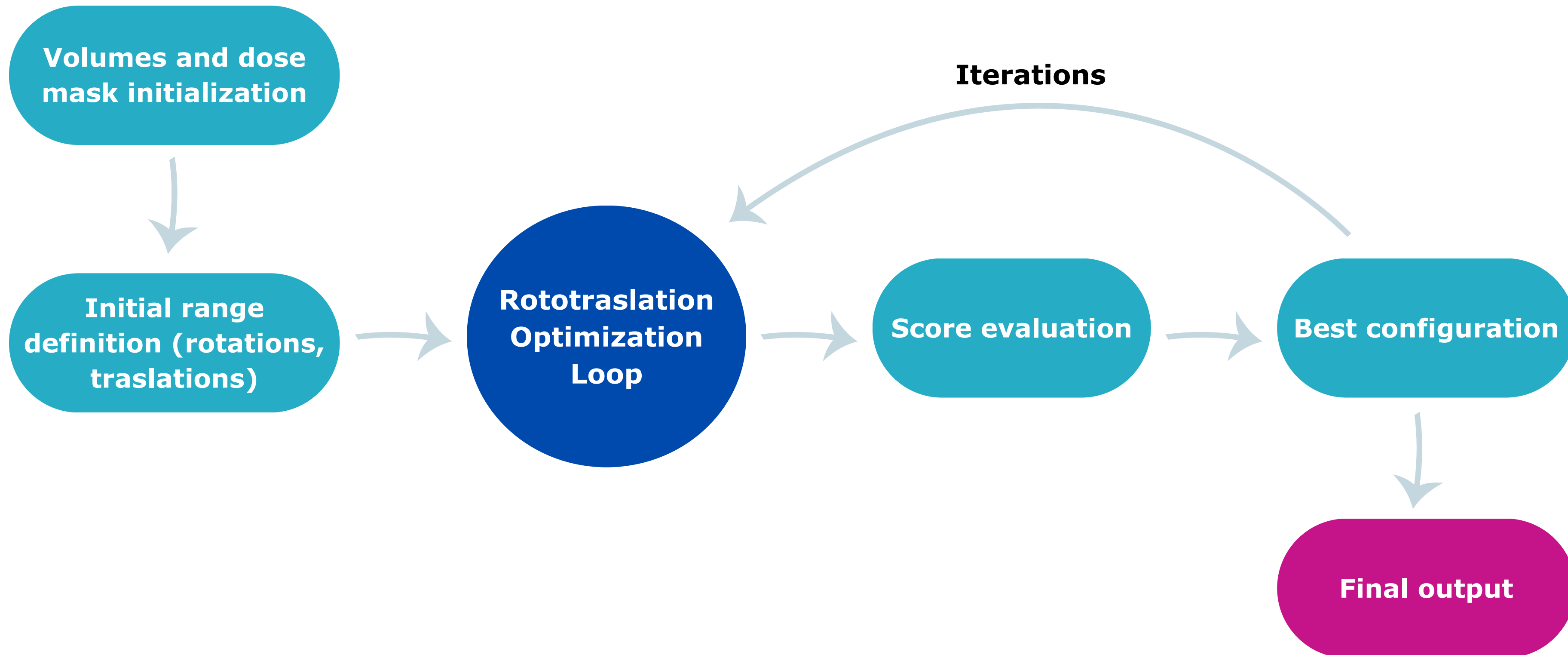
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Space Configurations explorations



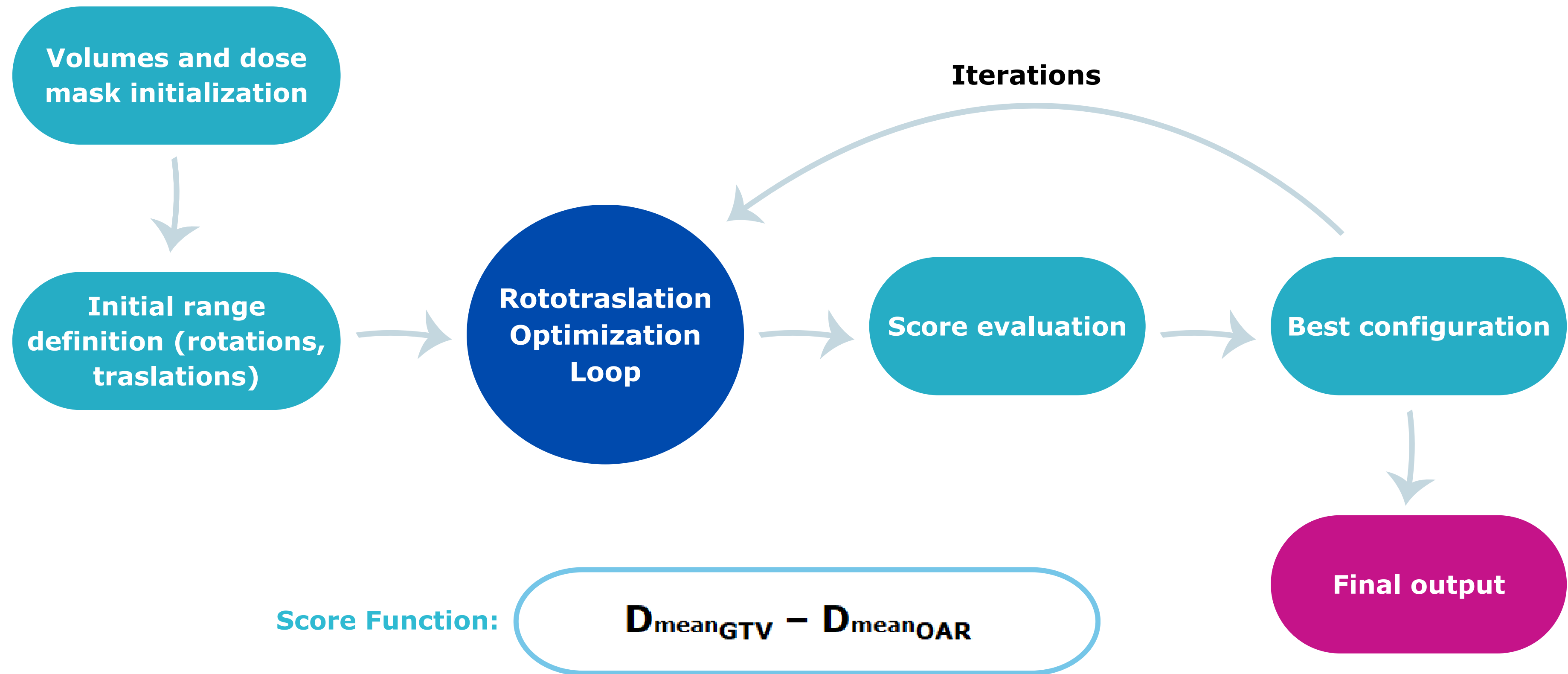
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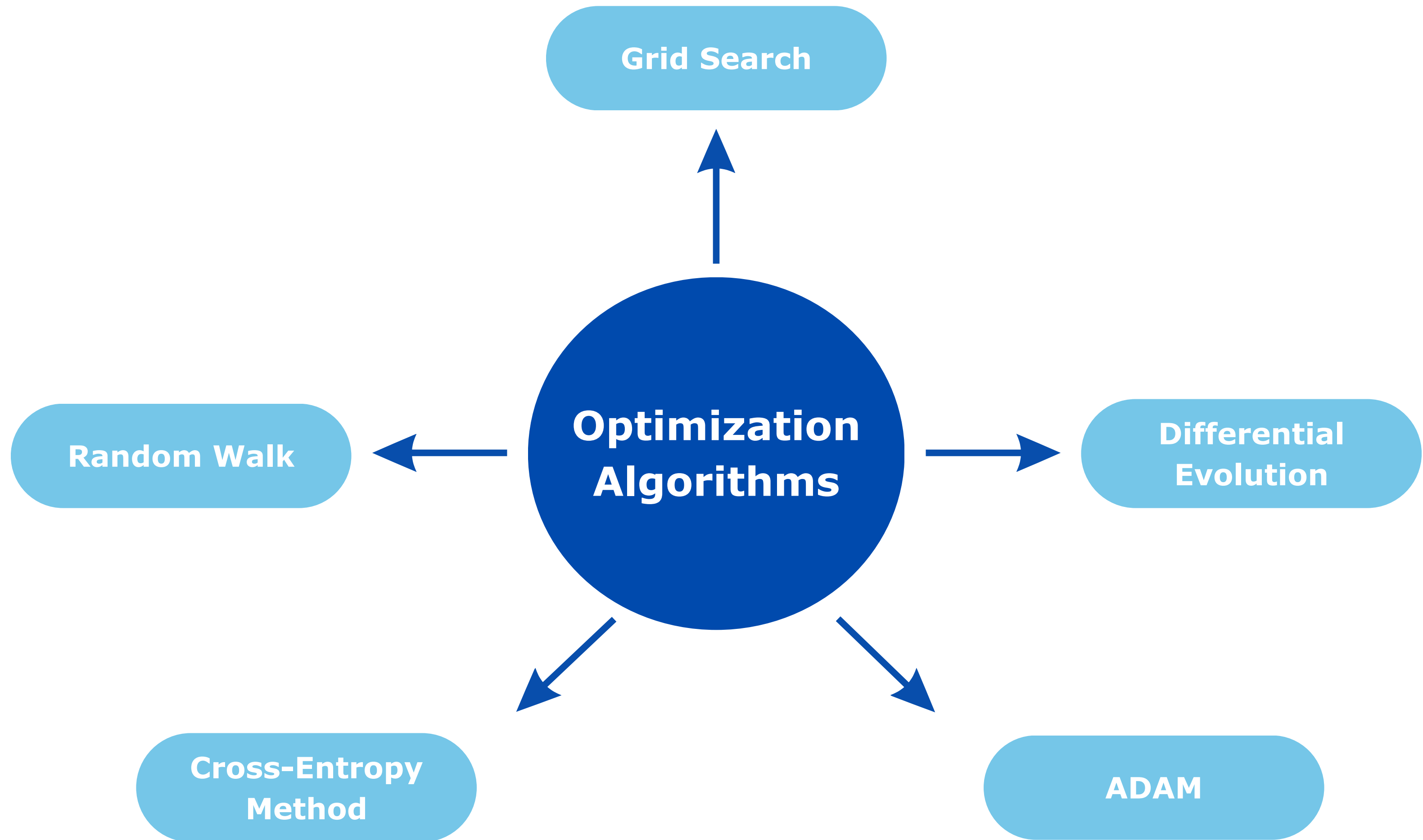
Space Configurations explorations



3

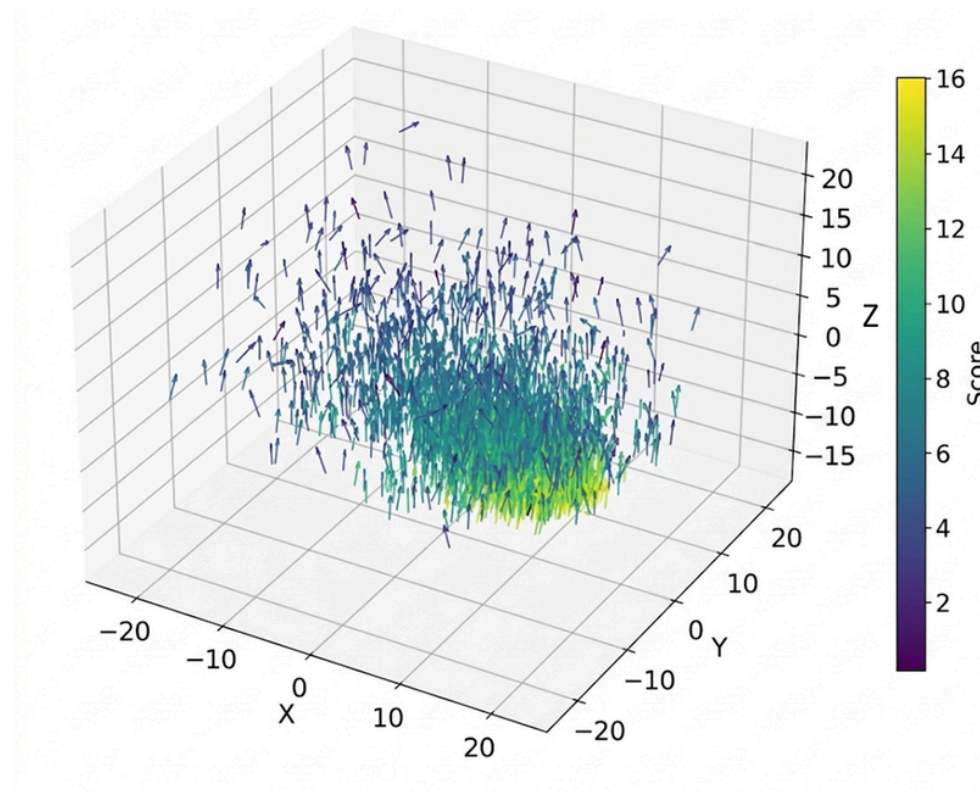
Space Configurations explorations



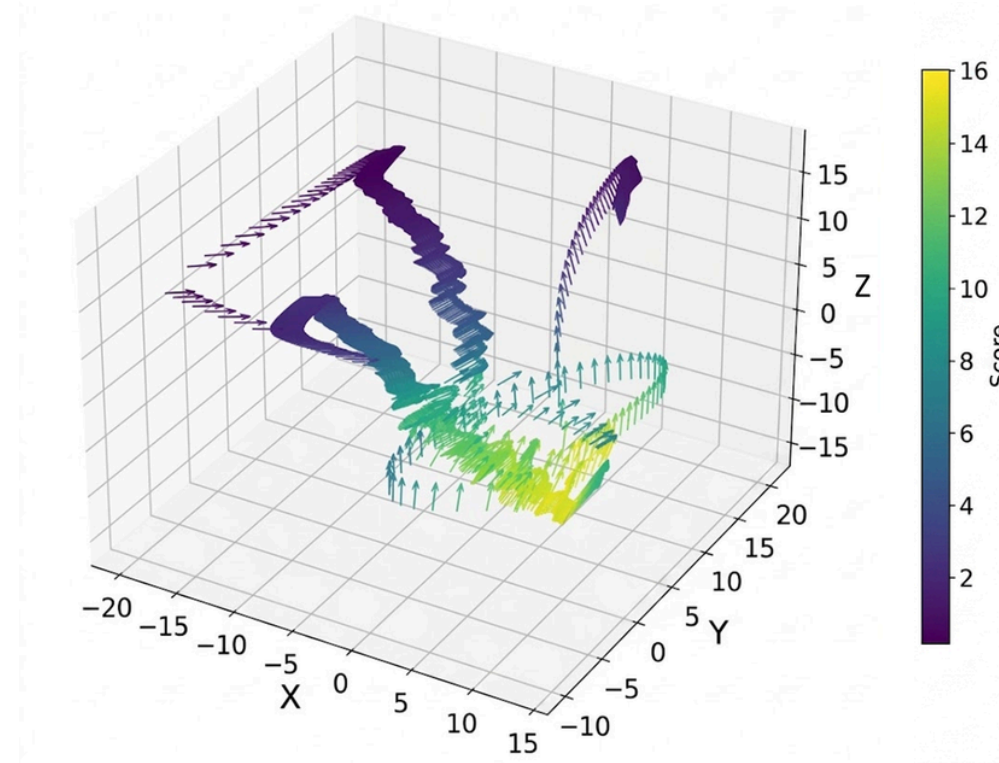


4 Results

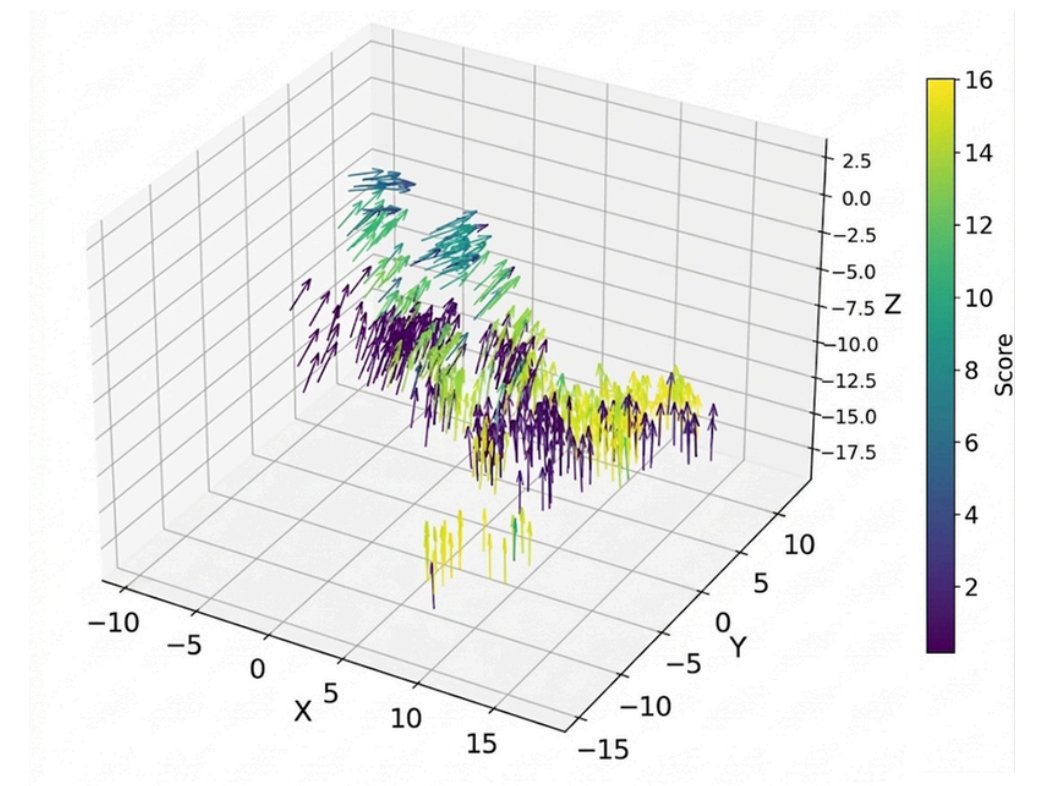
CROSS ENTROPY METHOD



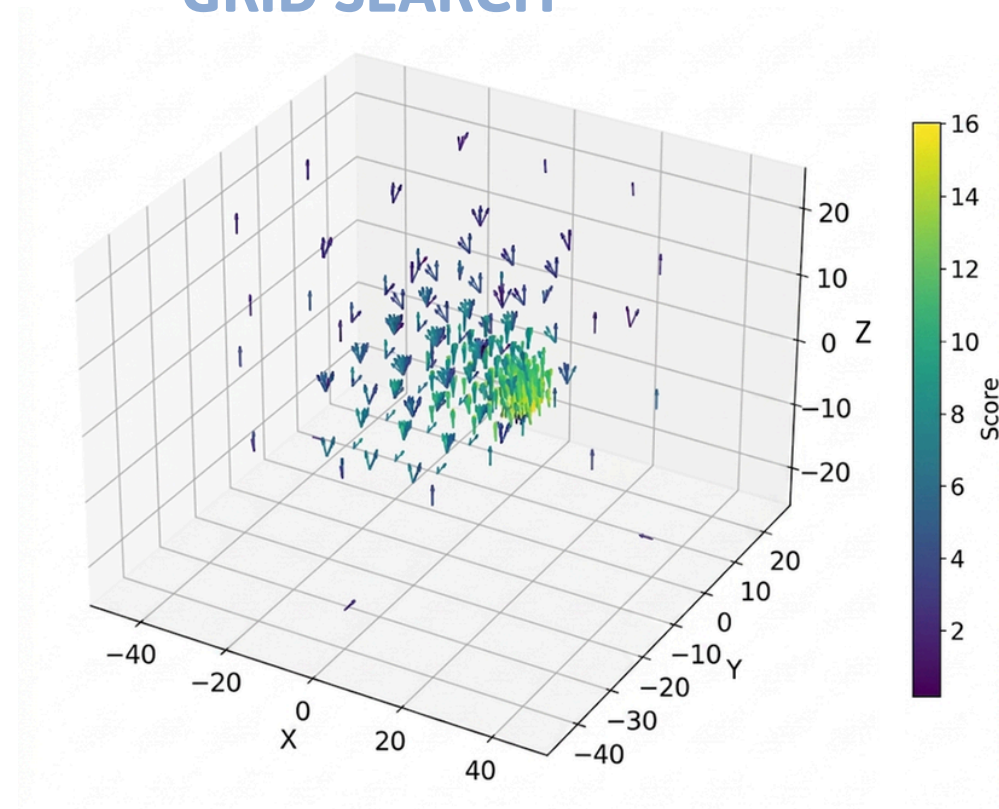
ADAM



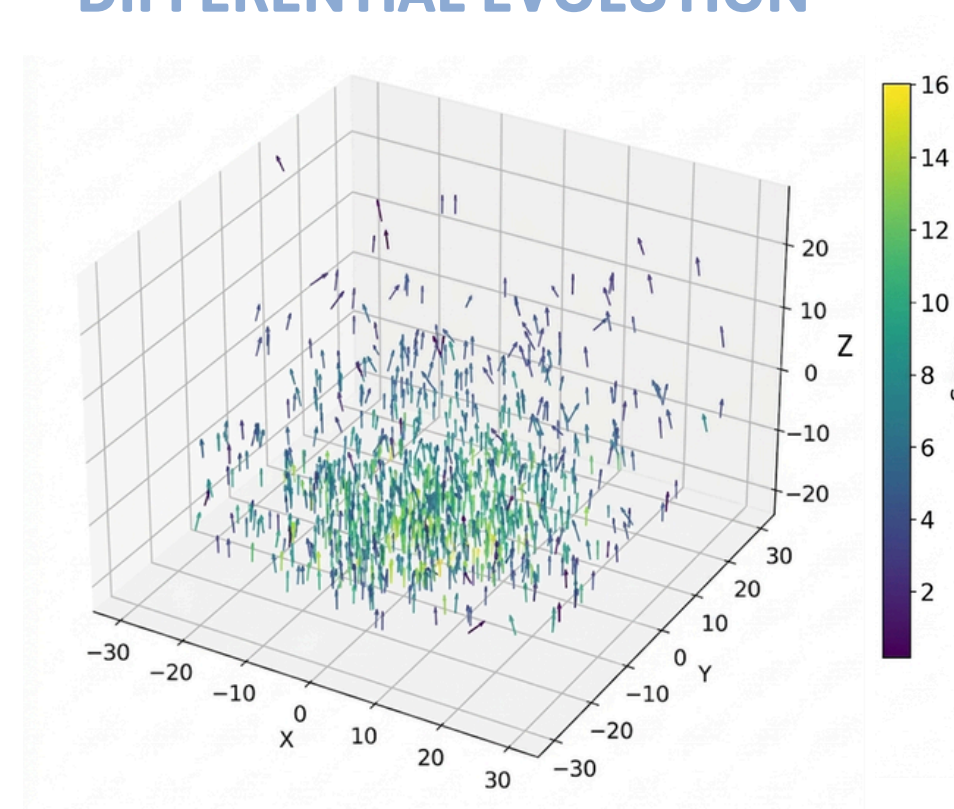
RANDOM WALK



GRID SEARCH

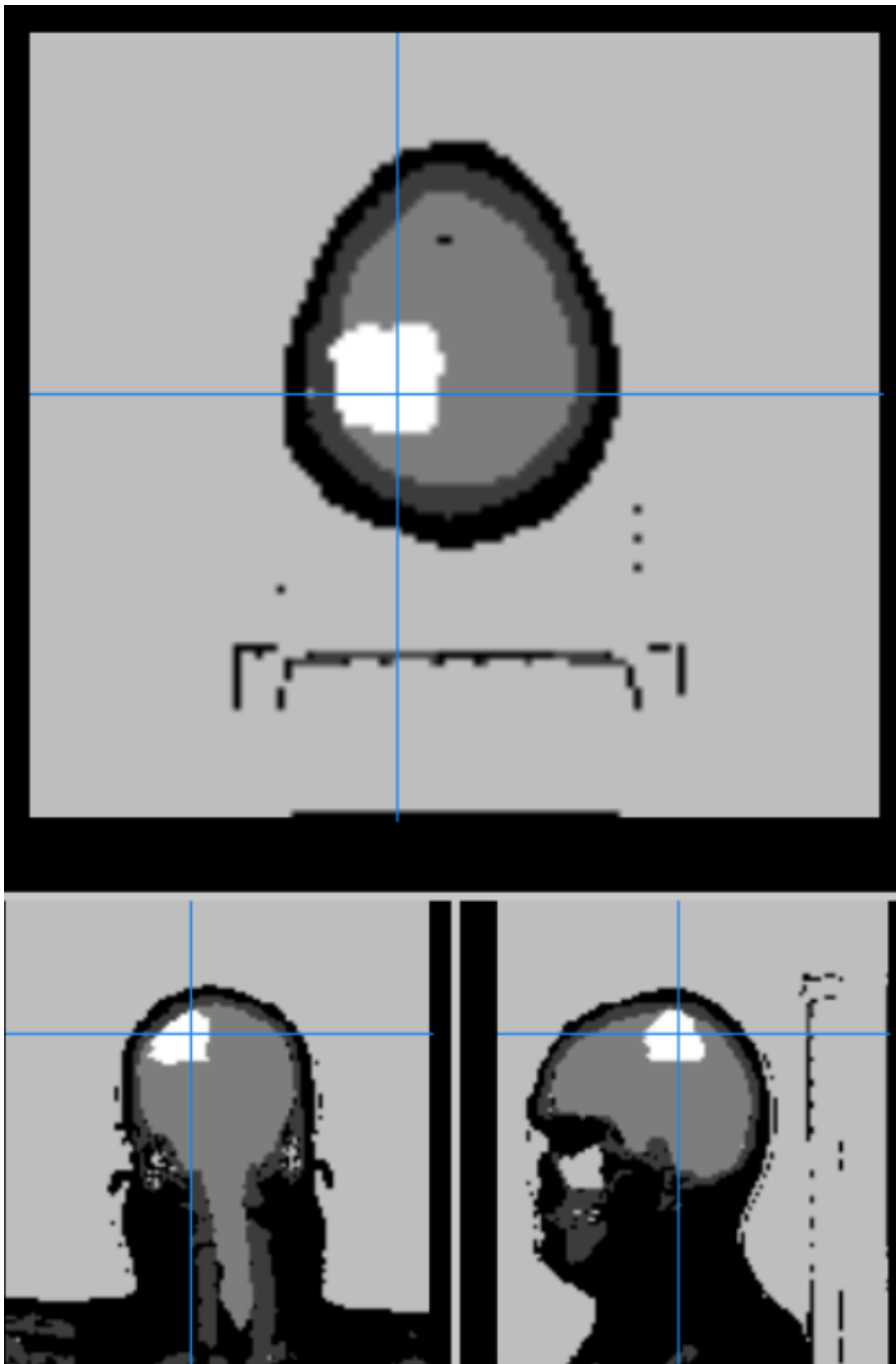


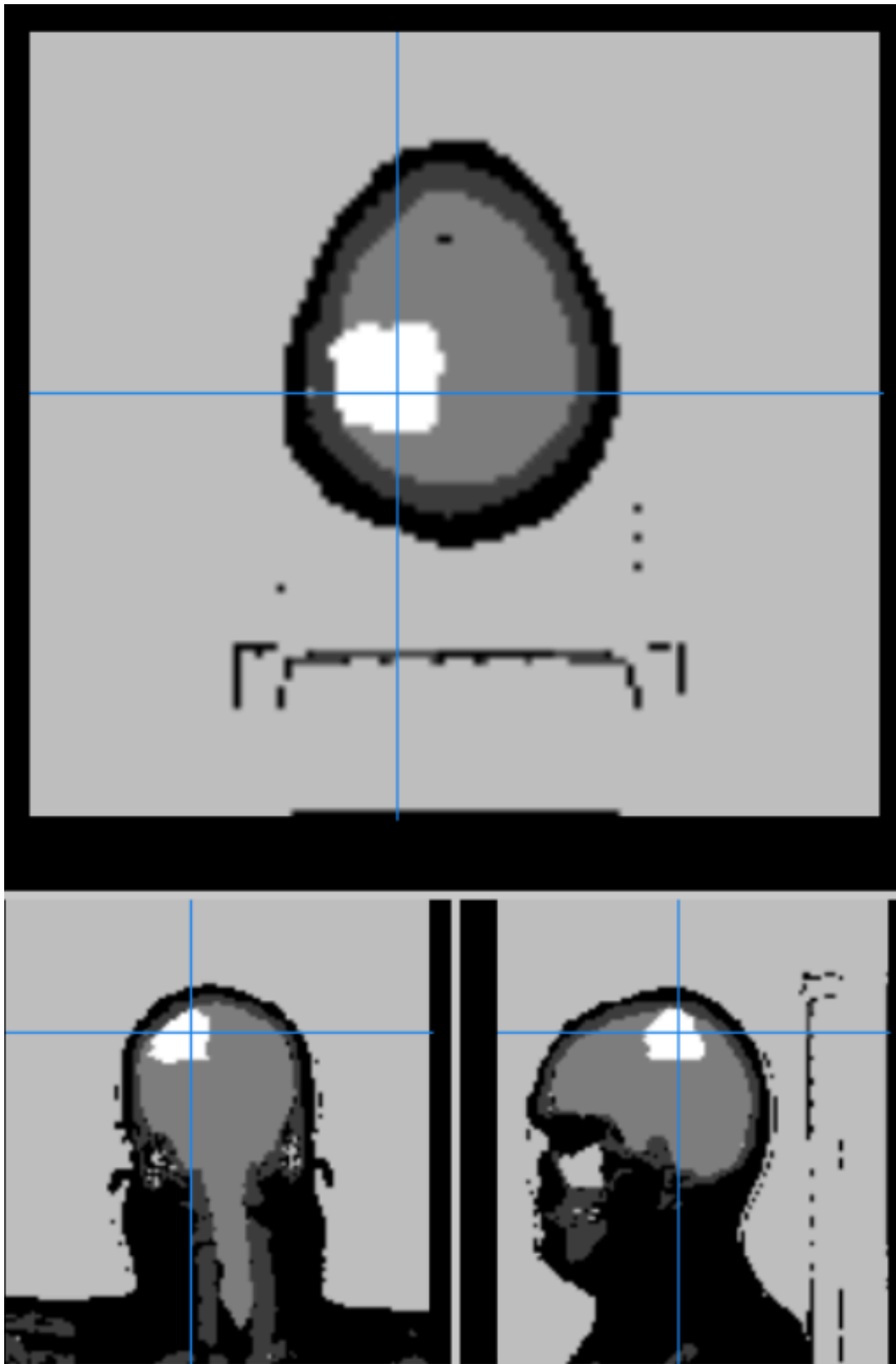
DIFFERENTIAL EVOLUTION



From Master's Degree
Thesis - Alessandra
Catania

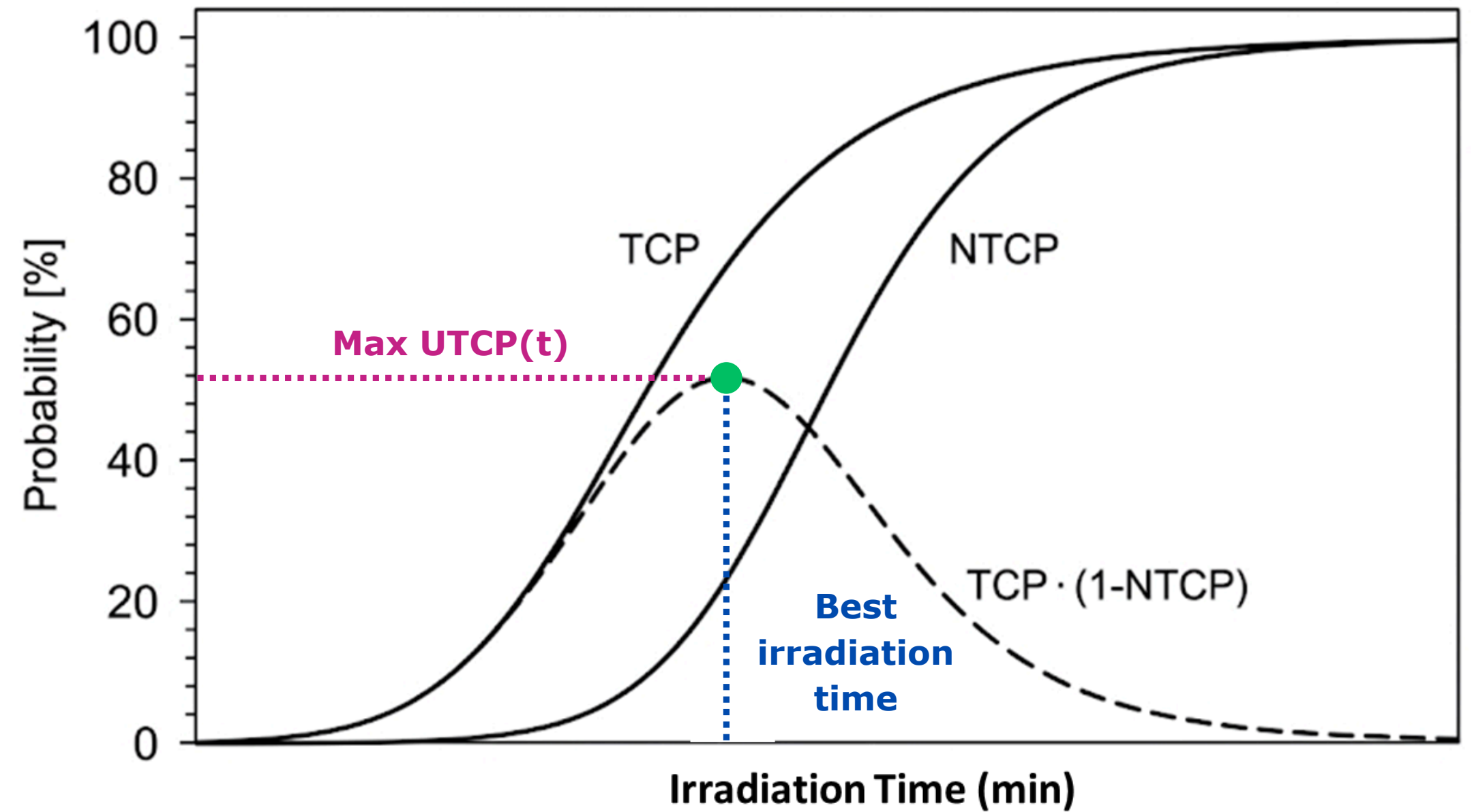
**Dosimetric
evaluation on a
patient**

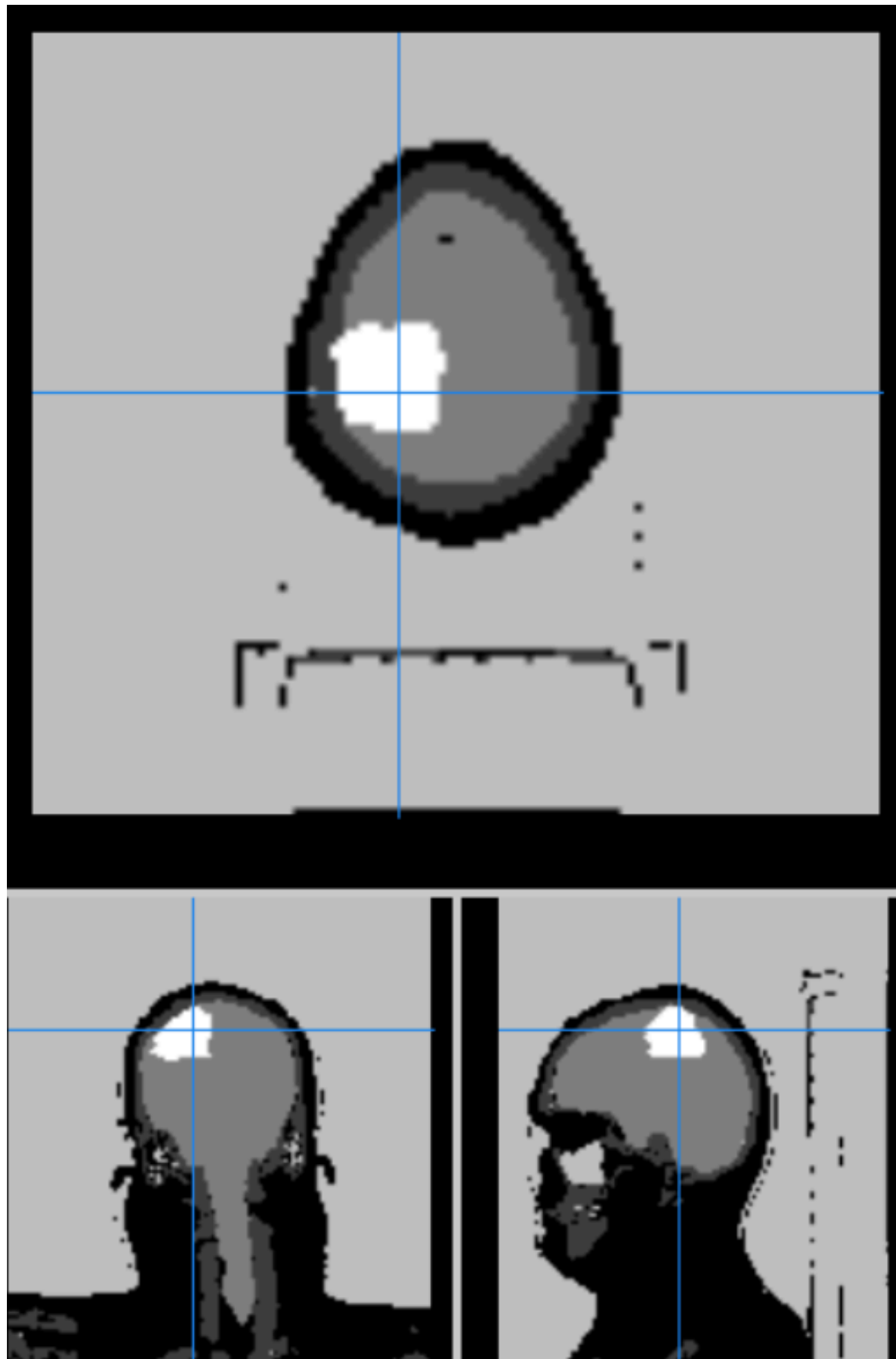




Score Function: UTCP

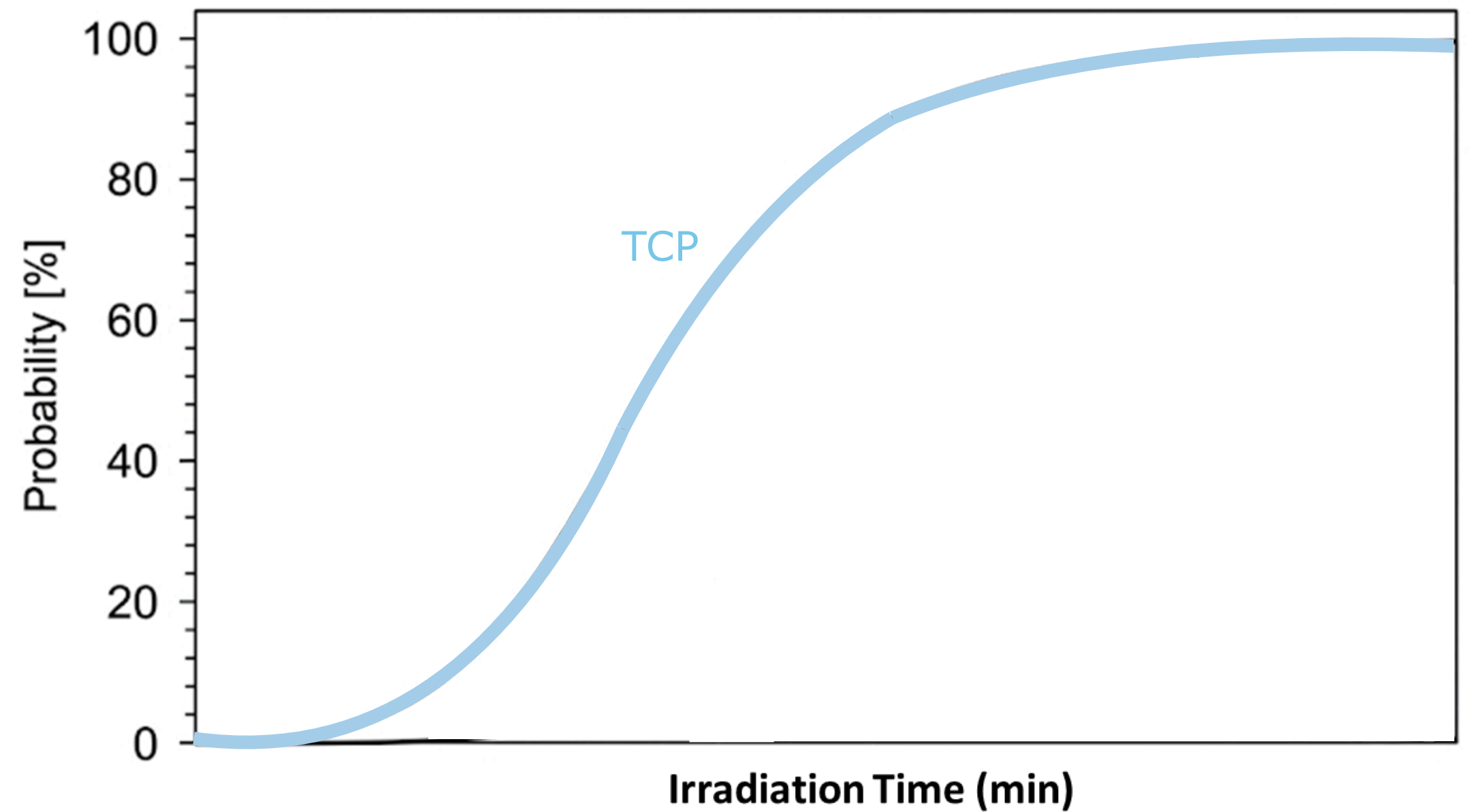
$$\text{UTCP} = \text{TCP} \times (1 - \text{NTCP})$$

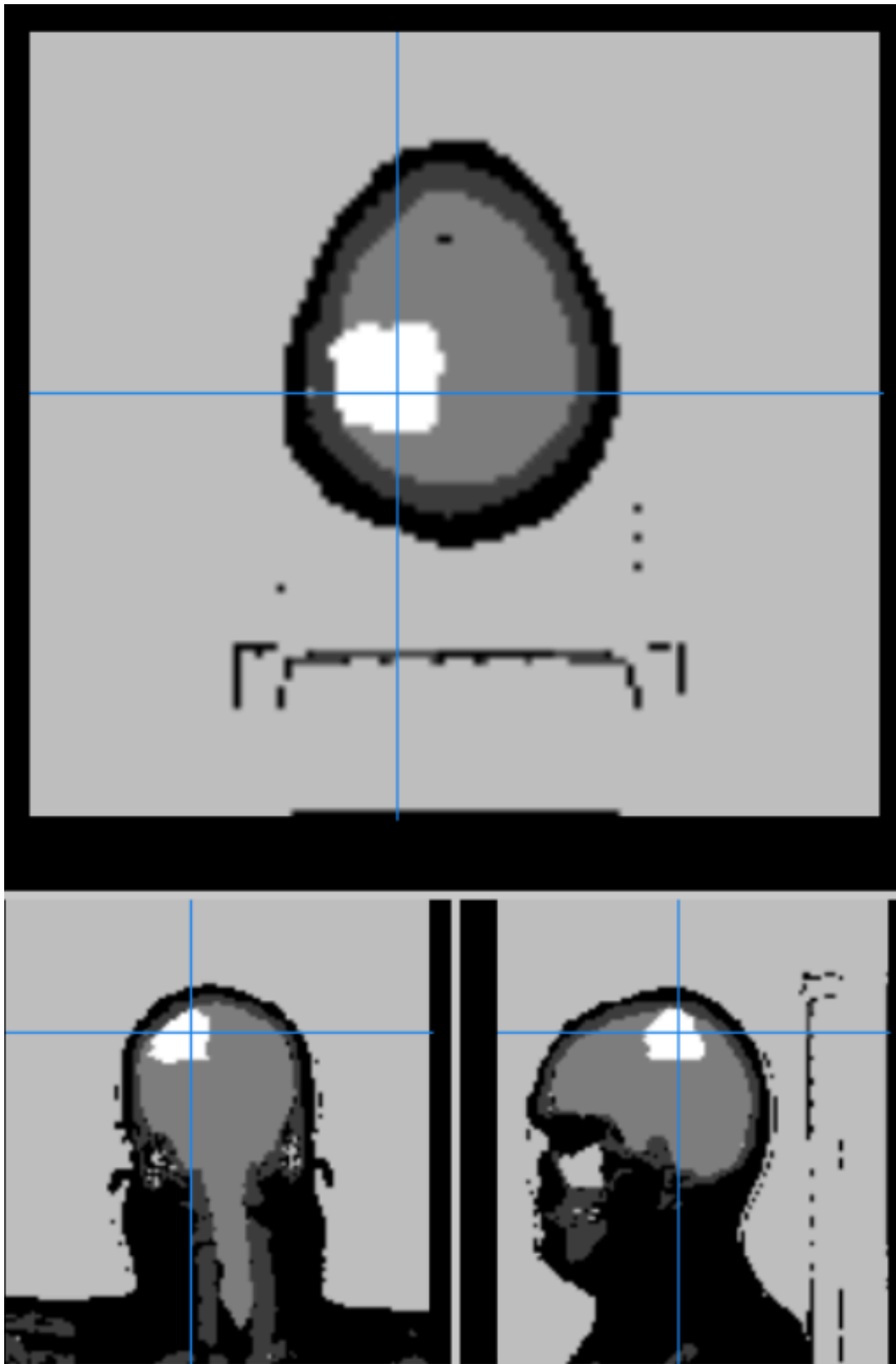




Score Function: UTCP

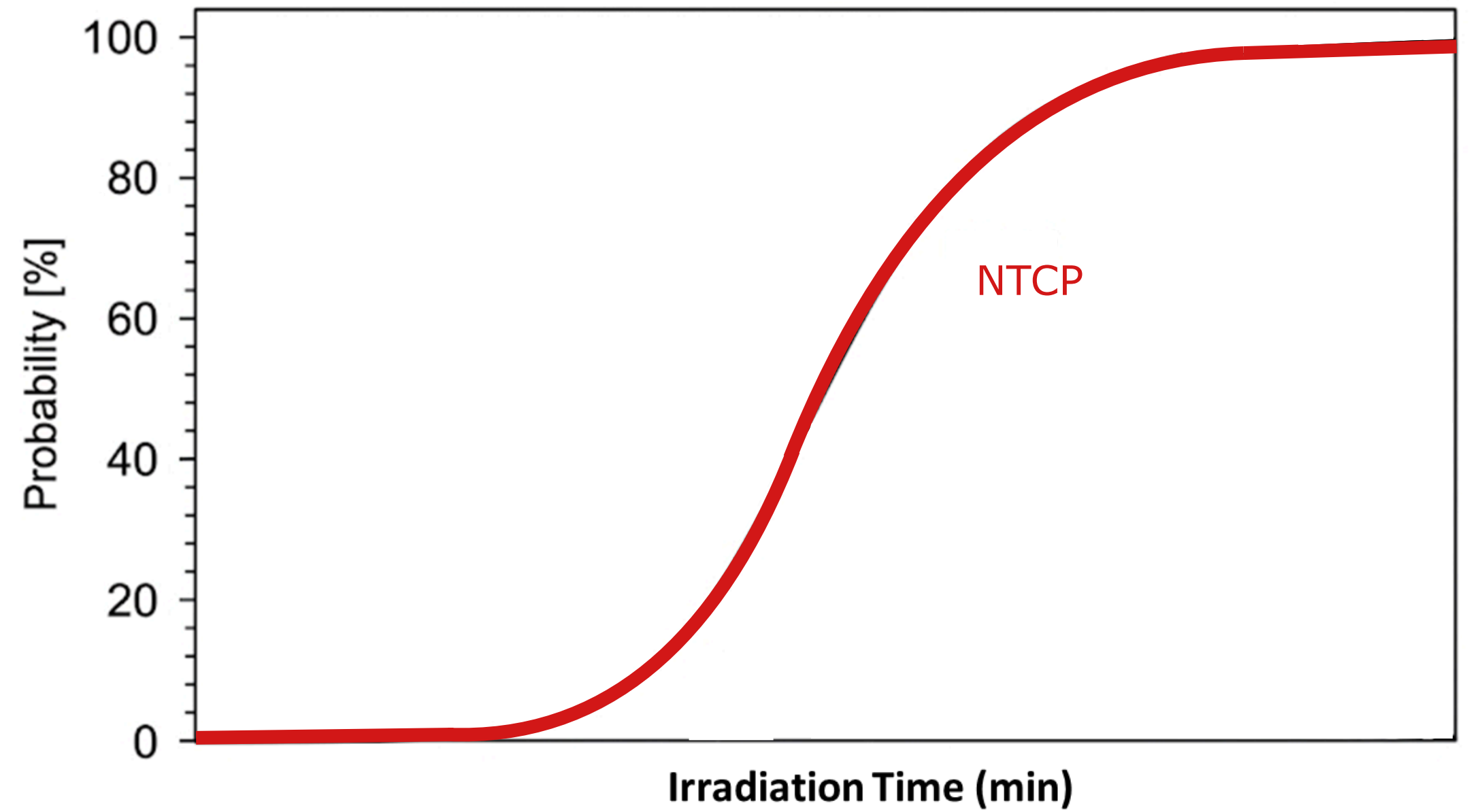
$$\text{UTCP} = \text{TCP} \times (1 - \text{NTCP})$$

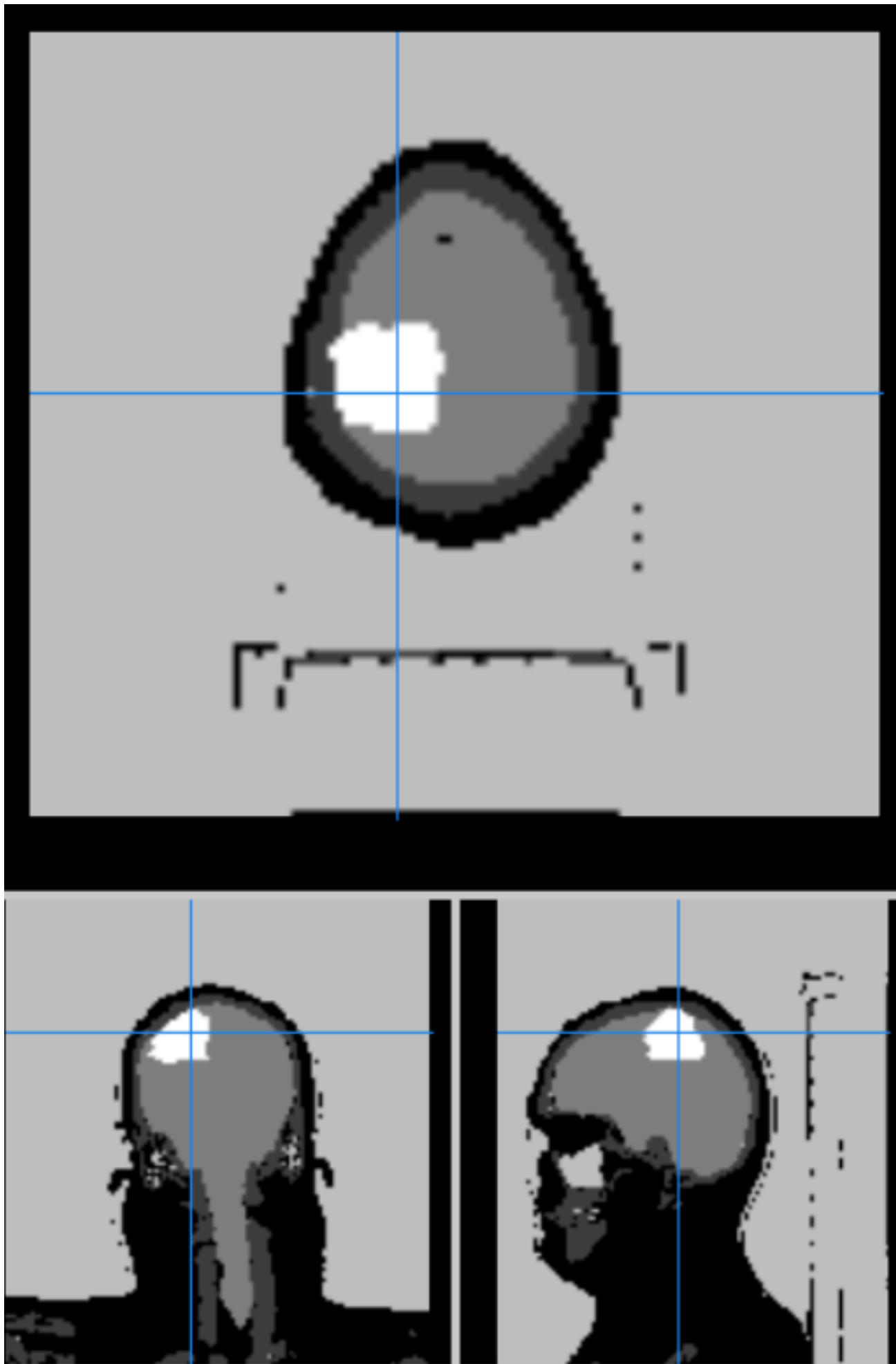




Score Function: UTCP

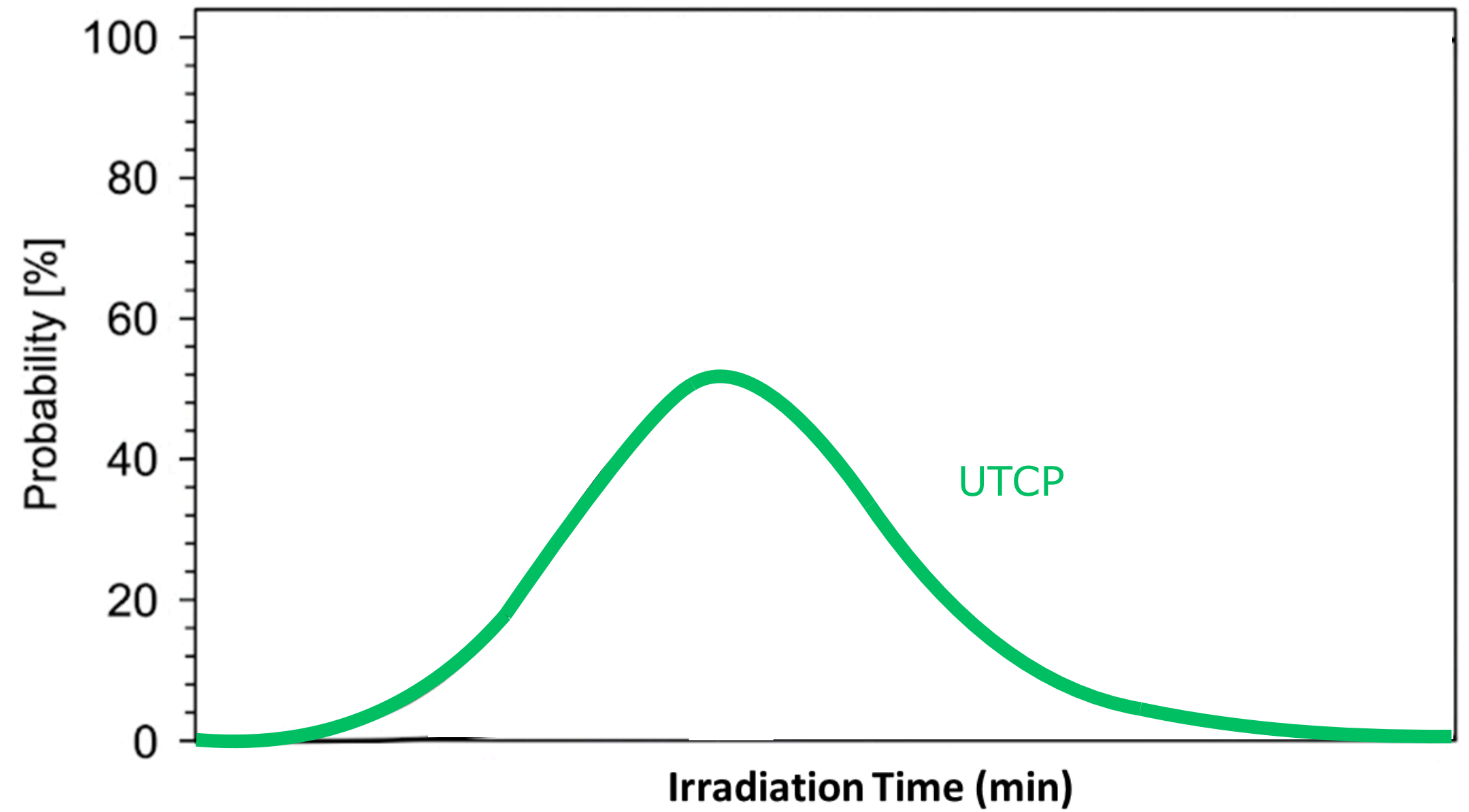
$$\text{UTCP} = \text{TCP} \times (1 - \text{NTCP})$$



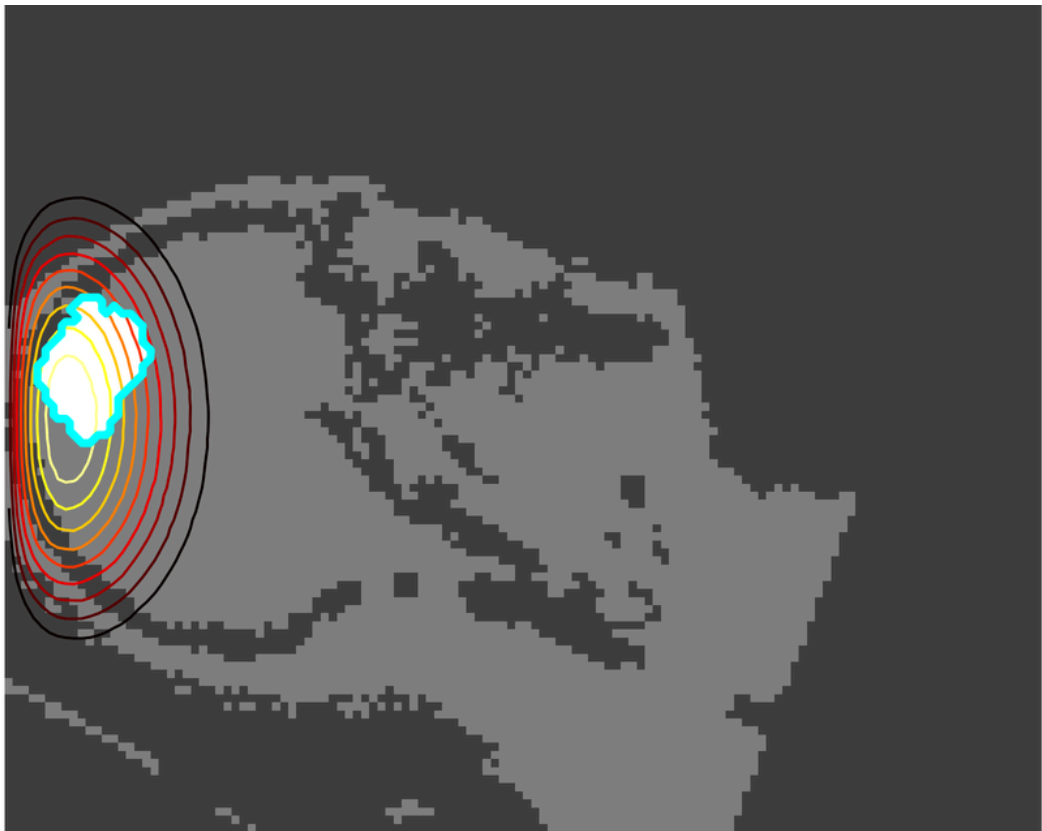


Score Function: UTCP

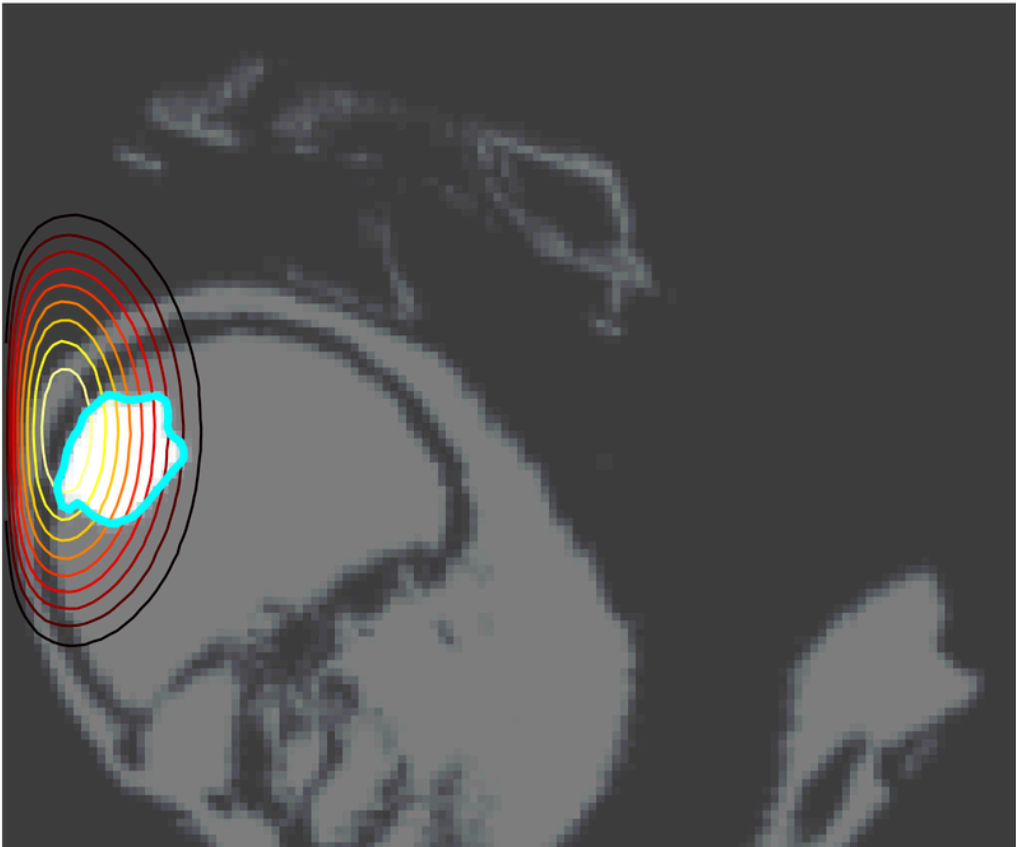
$$\text{UTCP} = \text{TCP} \times (1 - \text{NTCP})$$



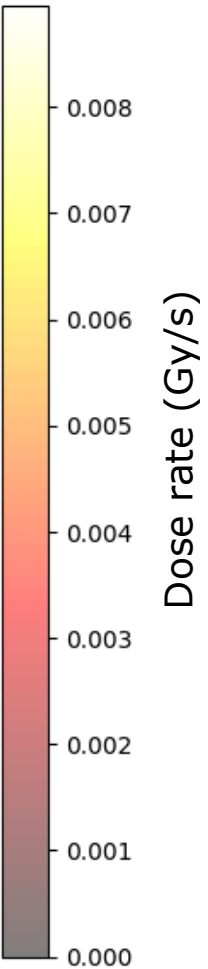
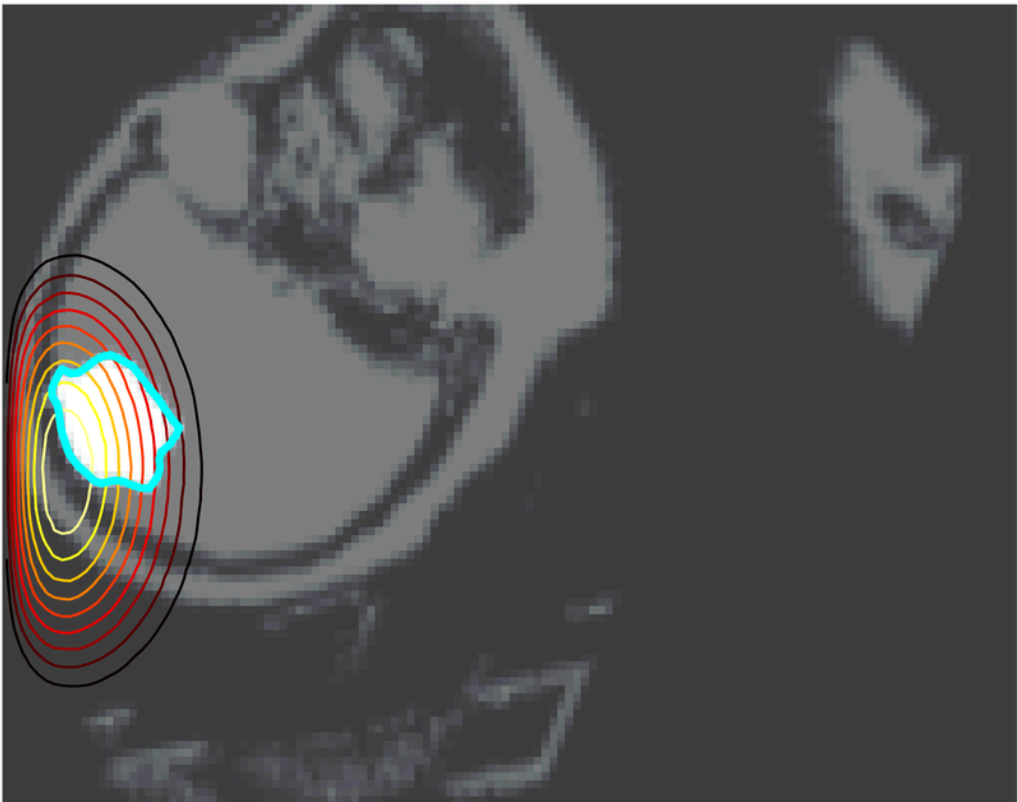
ADAM



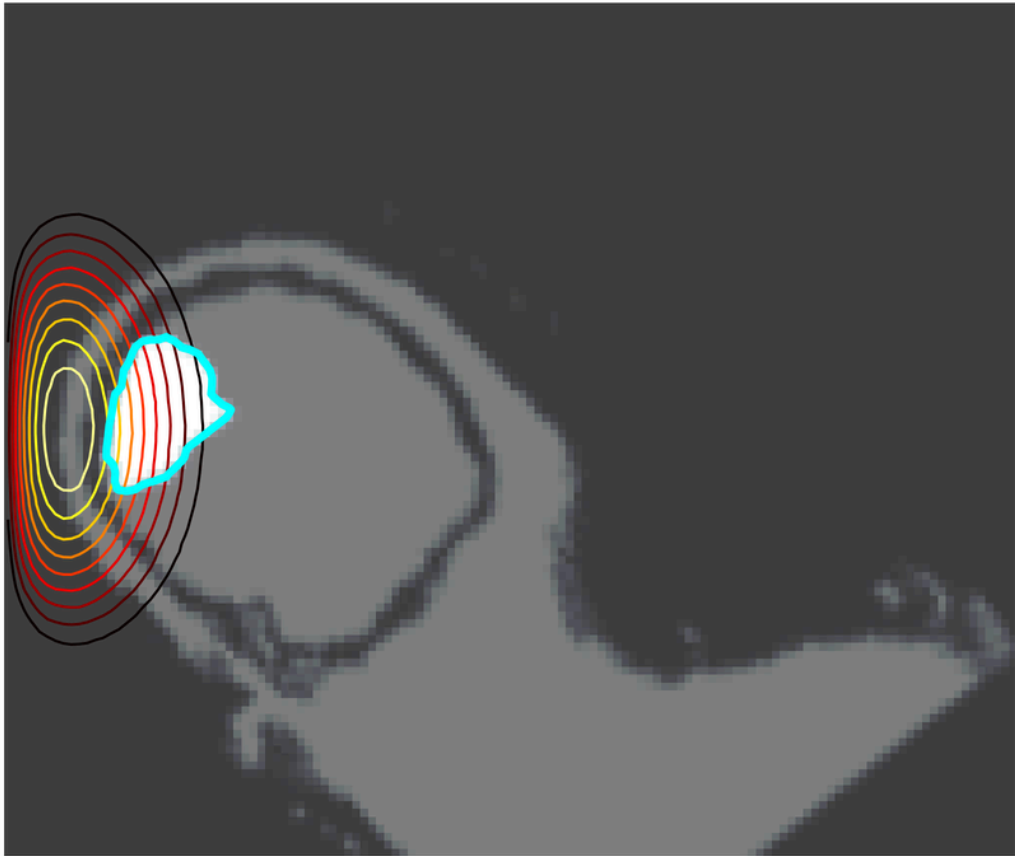
RANDOM WALK



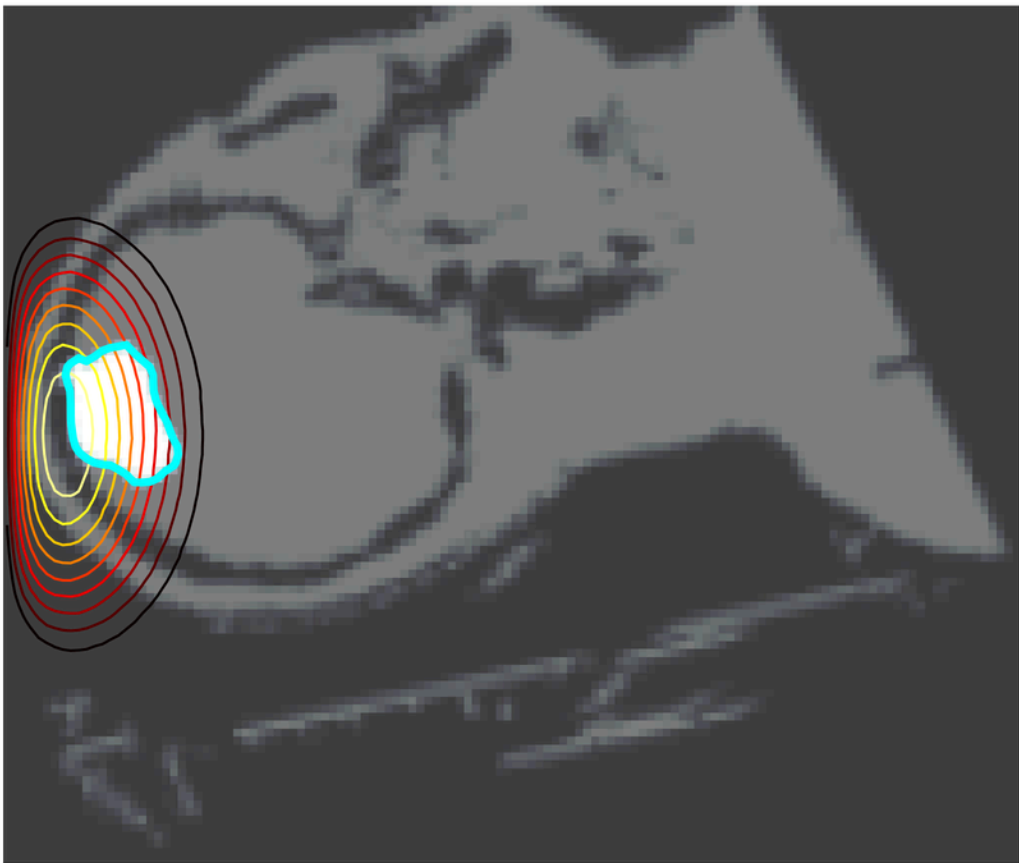
GRID SEARCH



CROSS ENTROPY METHOD

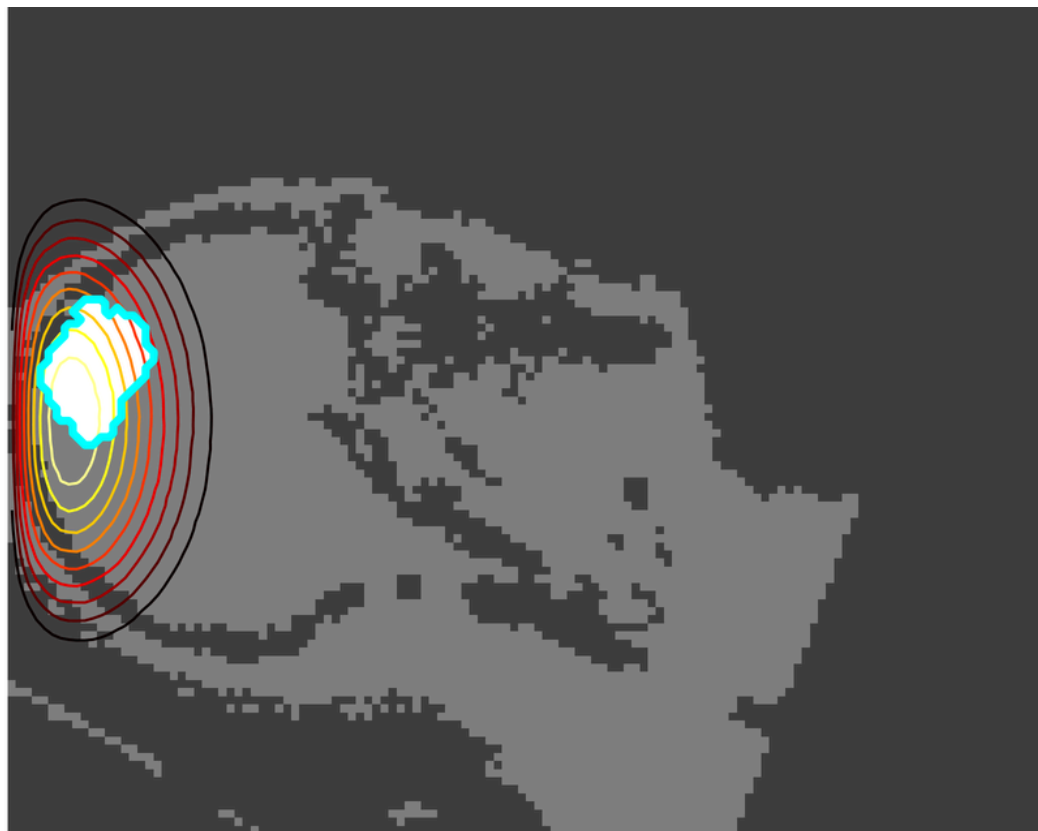


DIFFERENTIAL EVOLUTION

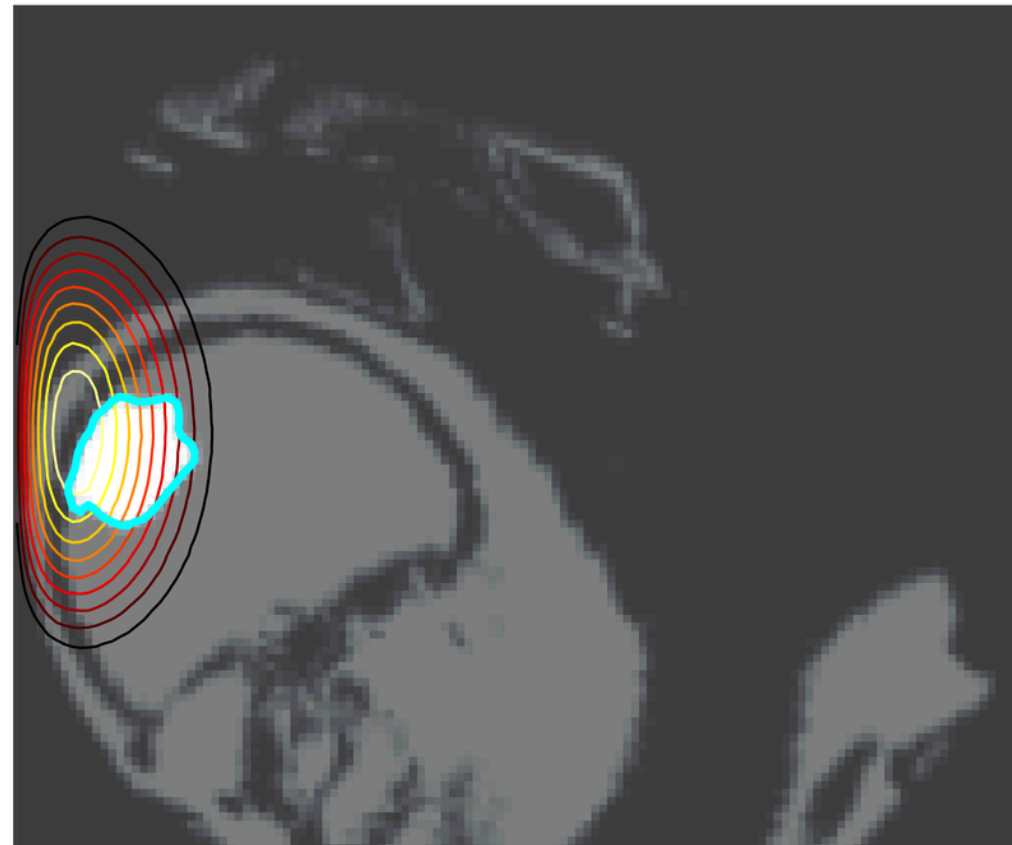


Method	Calculation Time
CEM	21 min 59 s
DE	17 min 5 s
GS	25 min 26 s
RW	6 min 16 s
ADAM	5 min 49 s

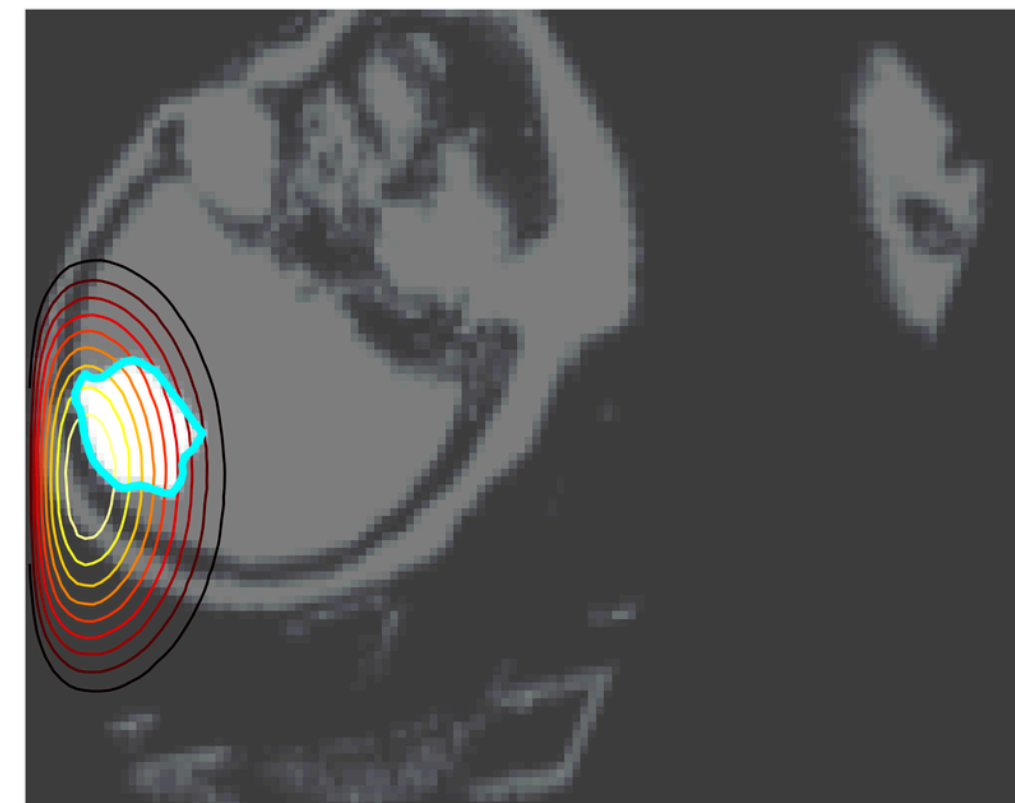
ADAM



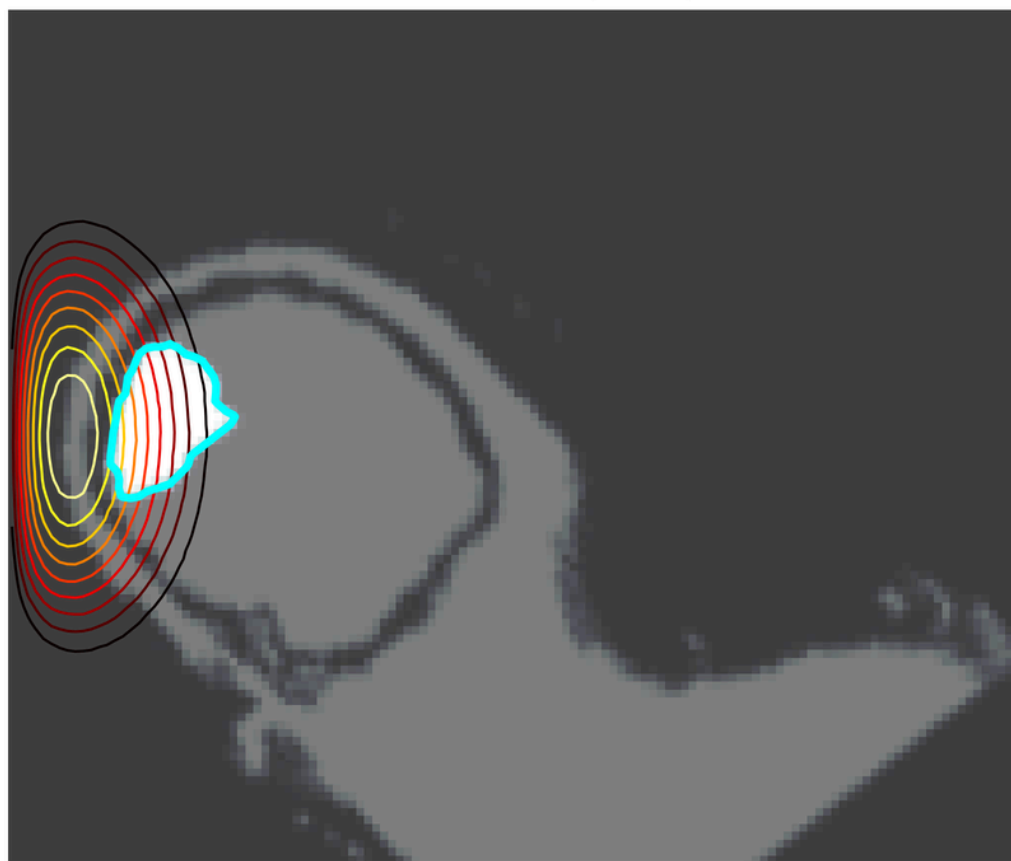
RANDOM WALK



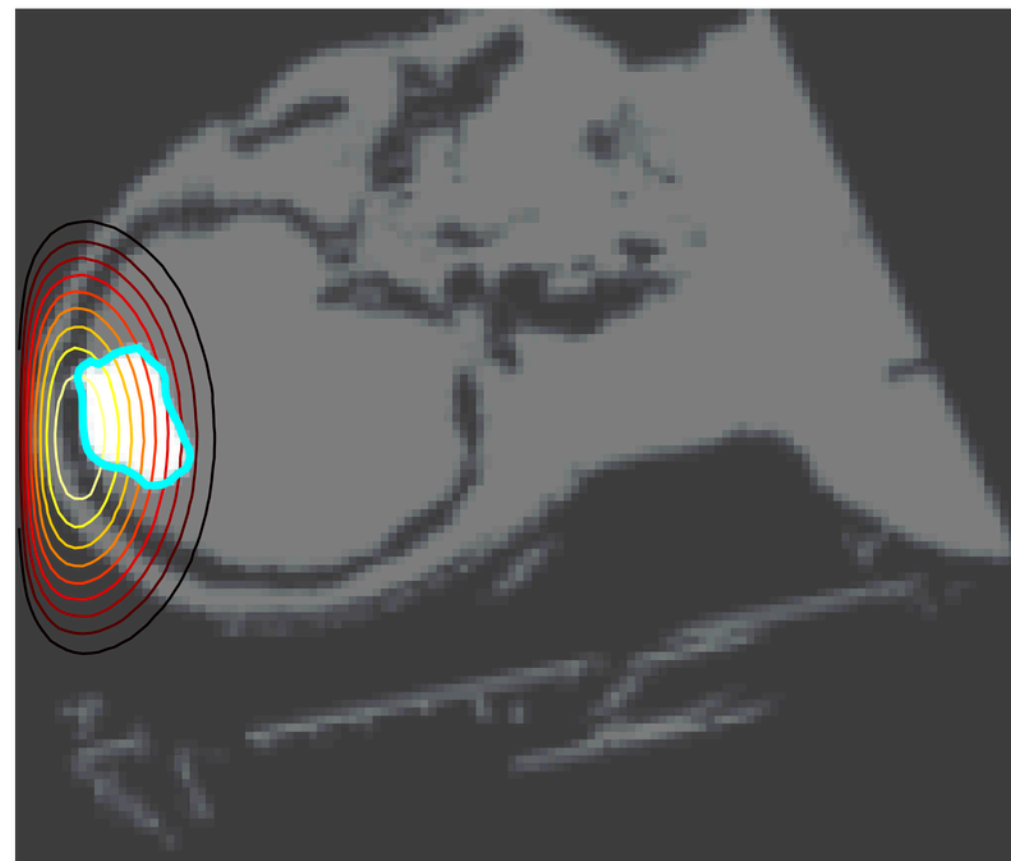
GRID SEARCH



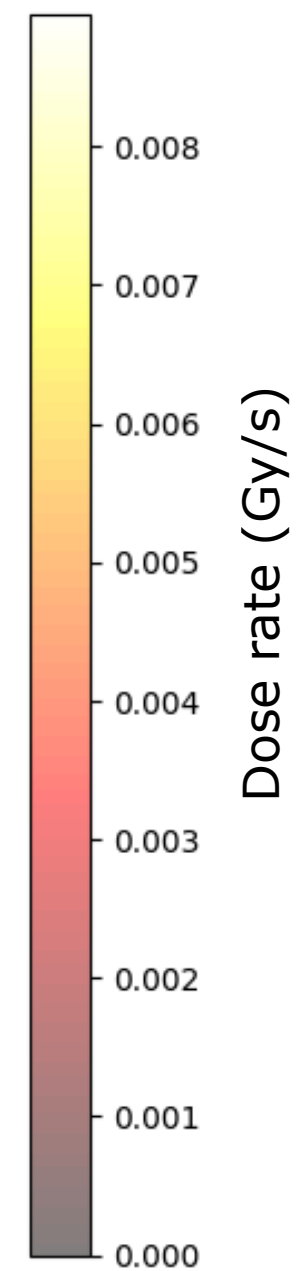
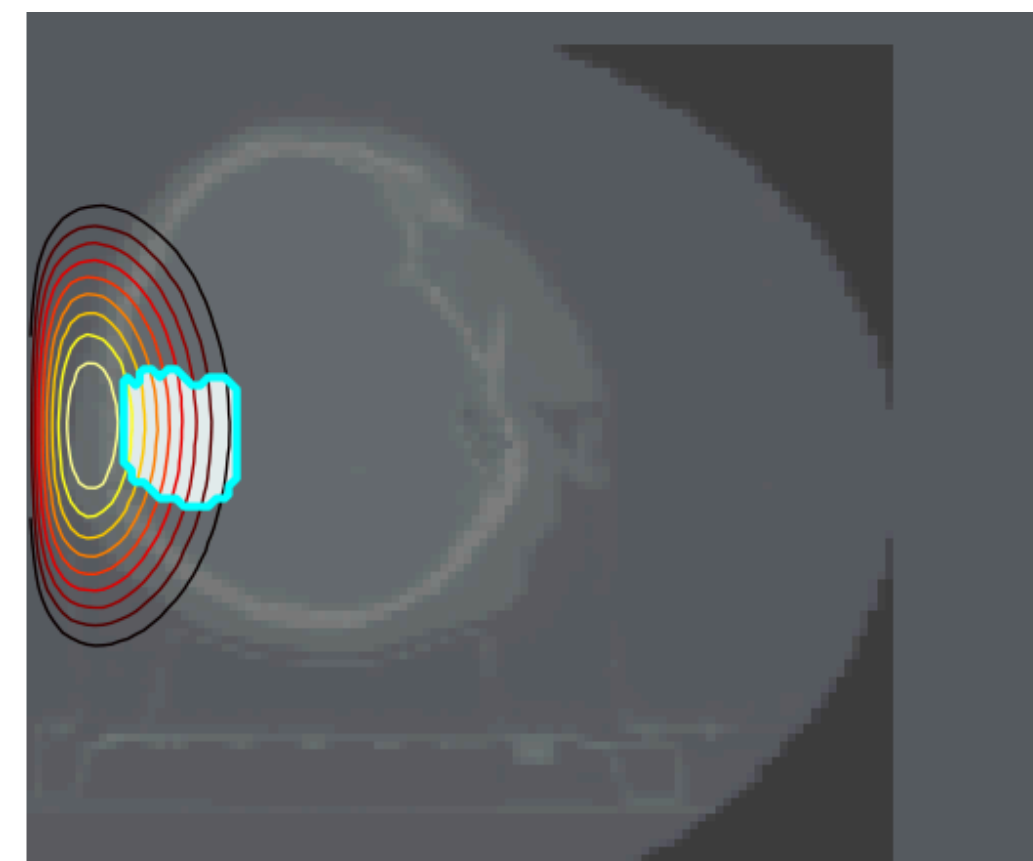
CROSS ENTROPY METHOD



DIFFERENTIAL EVOLUTION

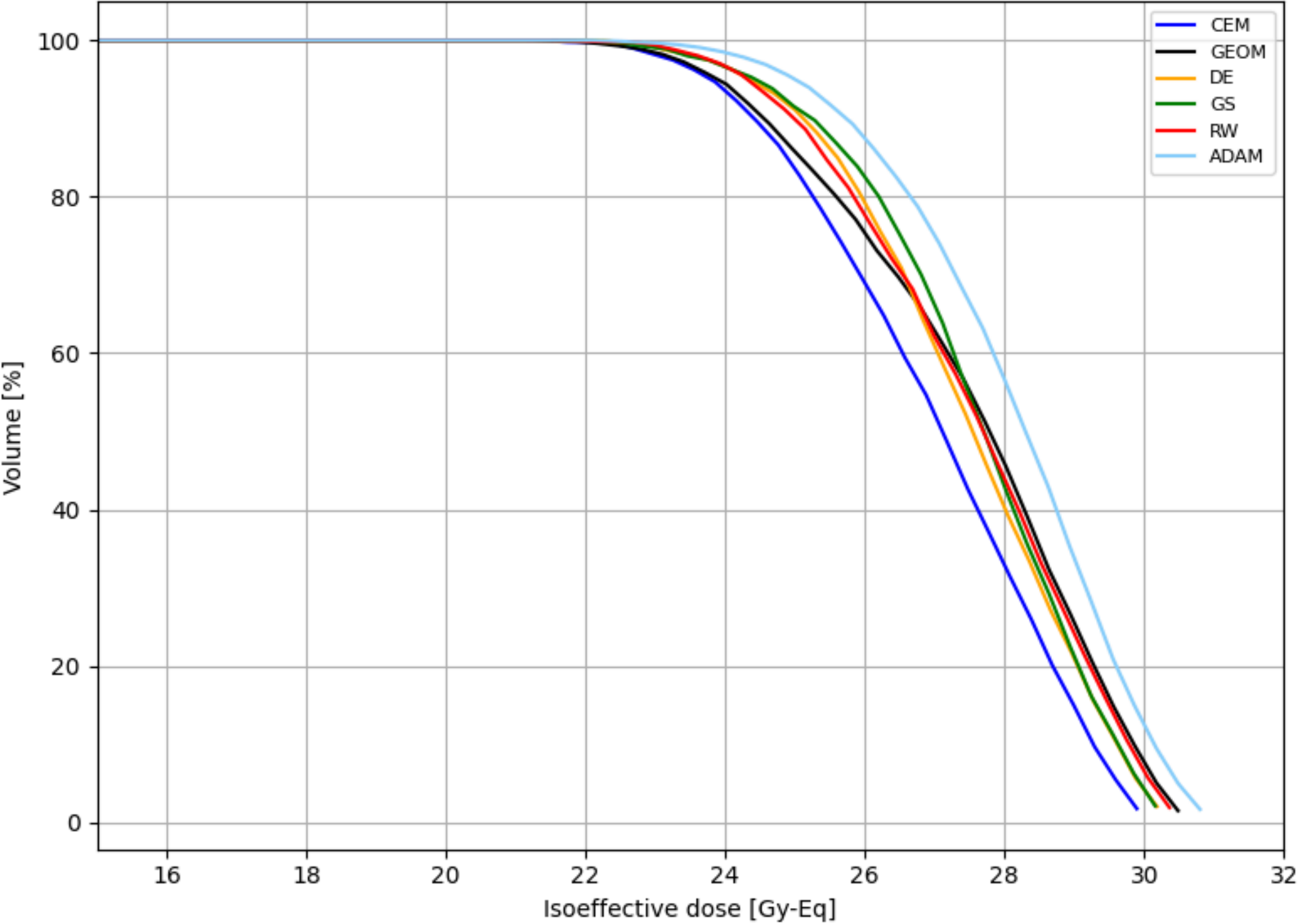


GEOMETRIC METHOD



Results

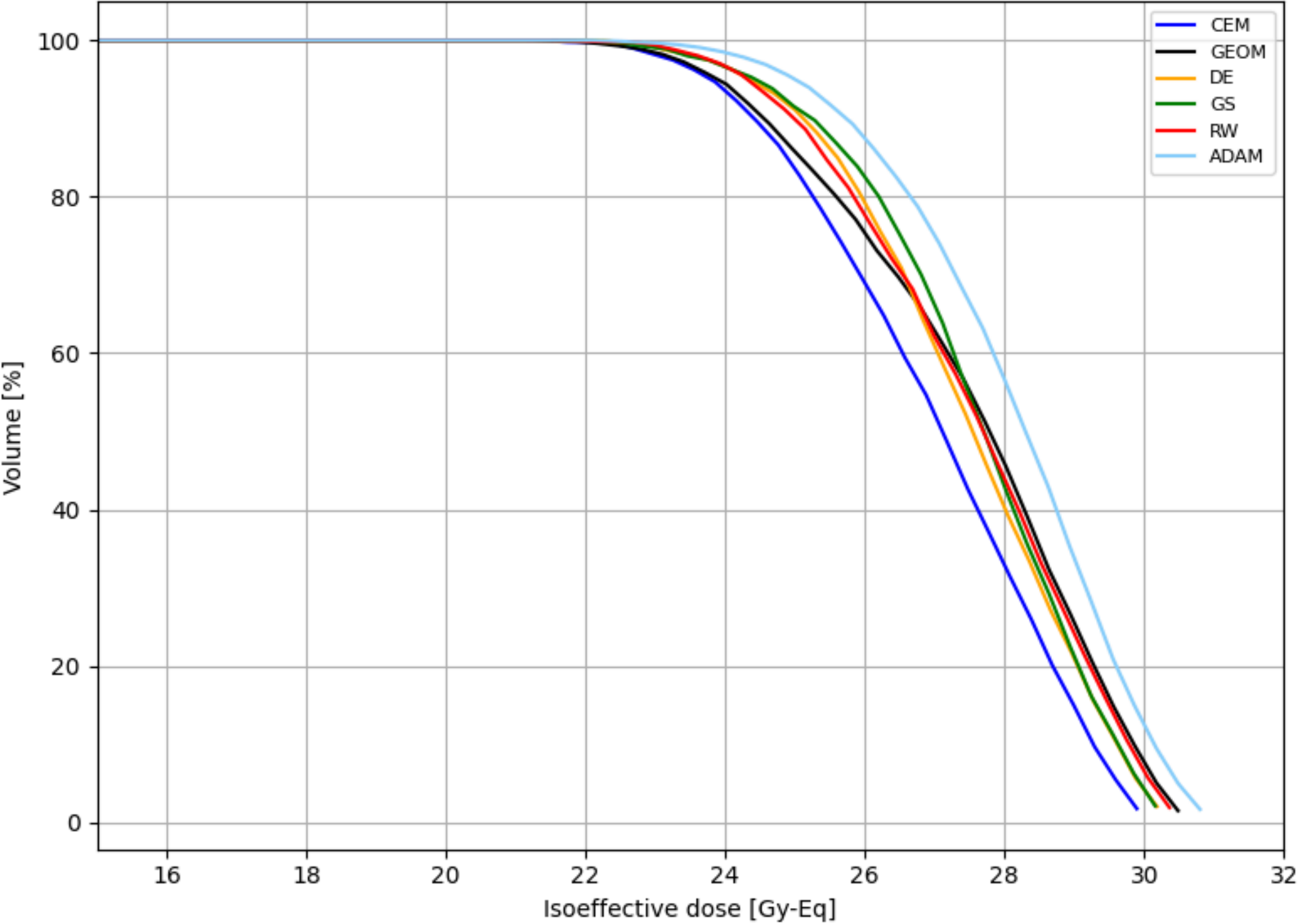
Dose Volume Histograms in GTV



Method	D98 [Gy-IsoE]	D50 [Gy-IsoE]	D2 [Gy-IsoE]
CEM	23,05	27,11	29,88
GEOM	23,17	27,78	30,44
GS	23,46	27,70	30,16
DE	23,54	27,54	30,18
RW	23,62	27,70	30,36
ADAM	24,19	28,30	30,77

Results

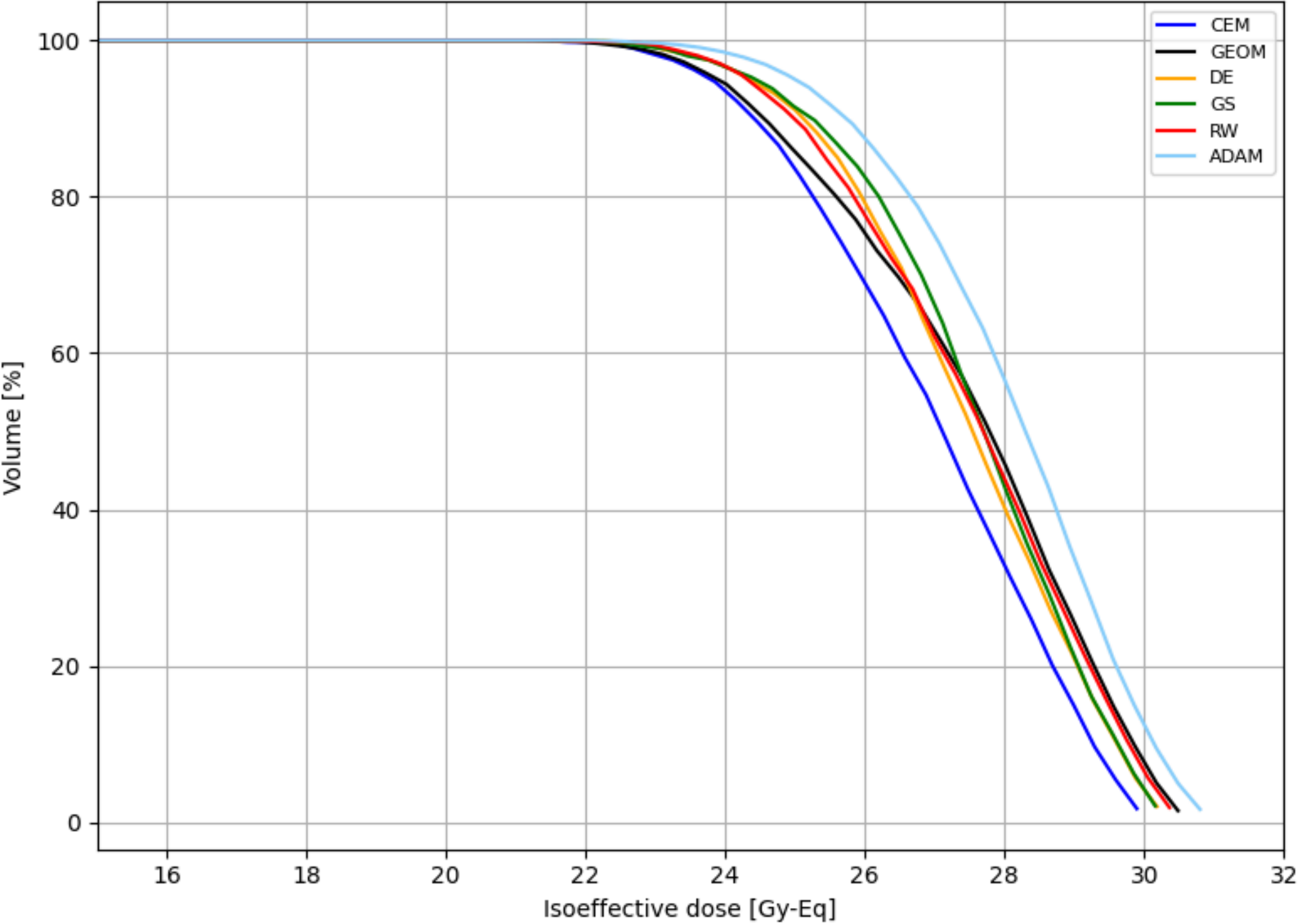
Dose Volume Histograms in GTV



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ADAM	24,19	28,30	30,77

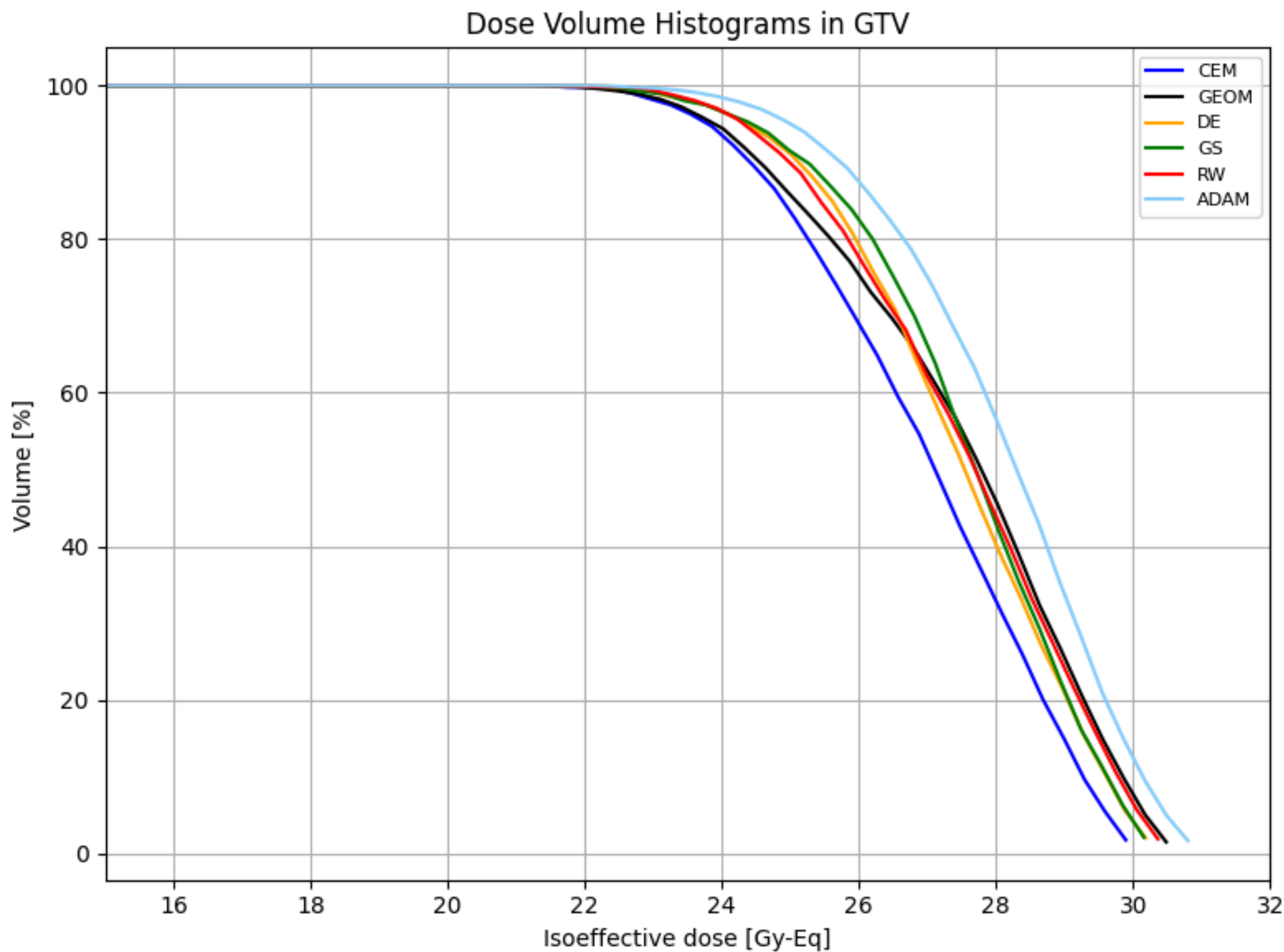
Results

Dose Volume Histograms in GTV



Method	D98 [Gy-IsoE]	D50 [Gy-IsoE]	D2 [Gy-IsoE]
CEM	23,05	27,11	29,88
GEOM	23,17	27,78	30,44
GS	23,46	27,70	30,16
DE	23,54	27,54	30,18
RW	23,62	27,70	30,36
ADAM	24,19	28,30	30,77

Results



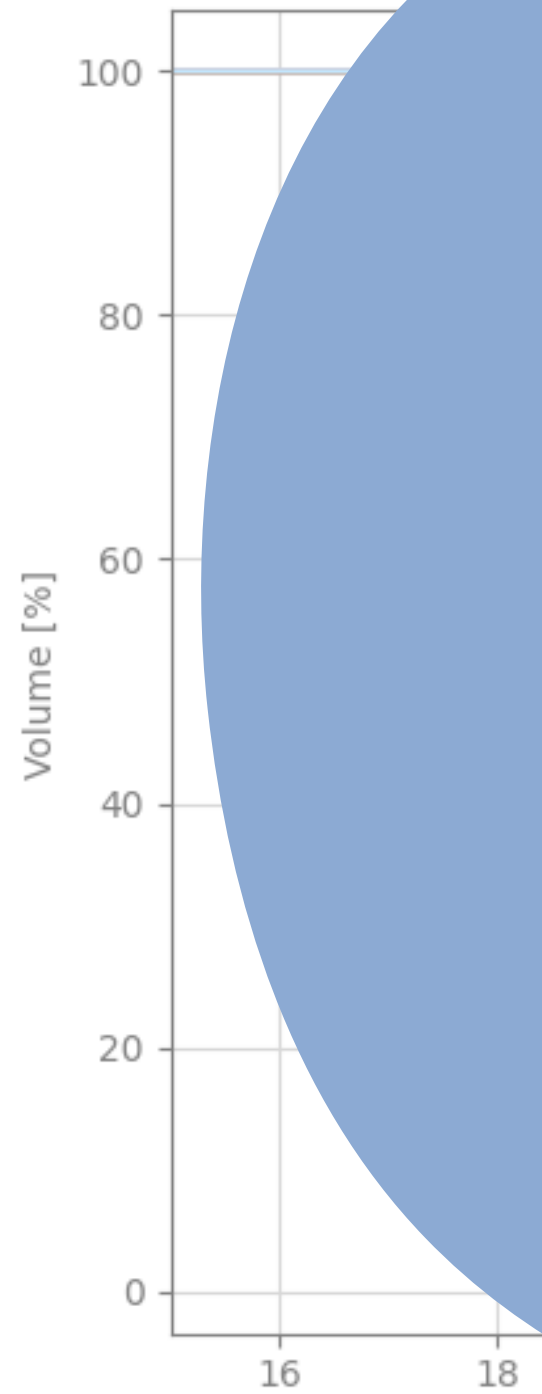
Average Slope = $\left| \frac{(D_{98} - D_2)}{(98 - 2)} \right|$

Method	Average Slope
CEM	0,0711
GEOM	0,0757
DE	0,0698
GS	0,0691
RW	0,0702
ADAM	0,0685

Results

$$\left| \frac{(D98 - D2)}{(98 - 2)} \right|$$

**CONSISTENT SPACE
RESEARCH AND
OUTCOMES**



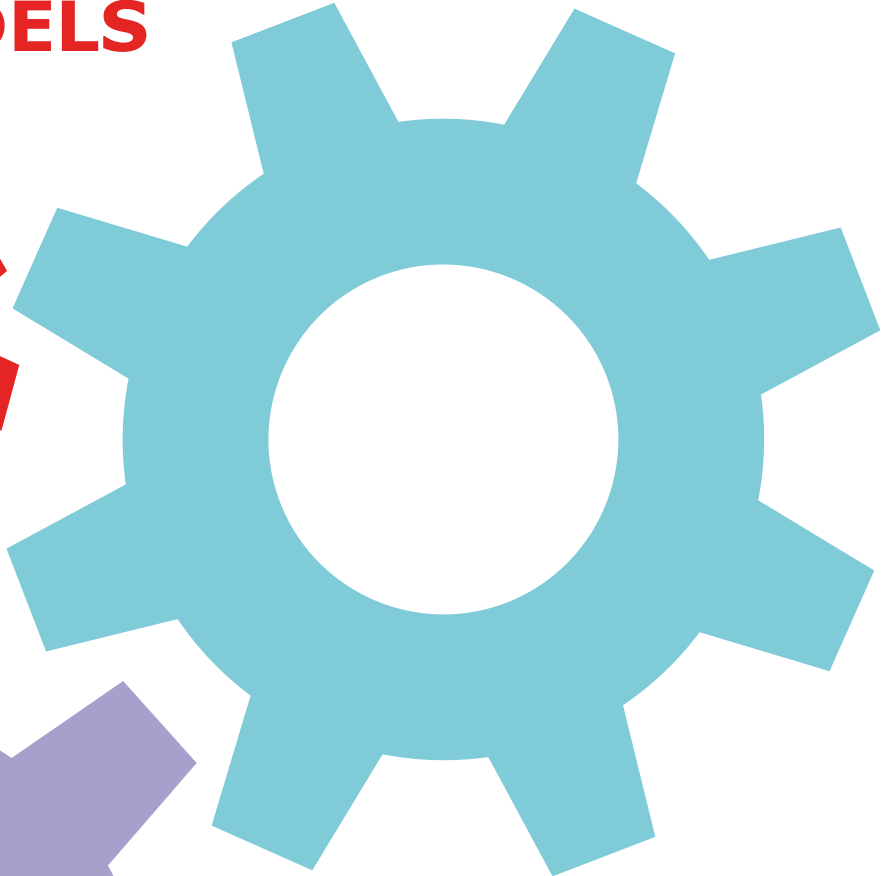
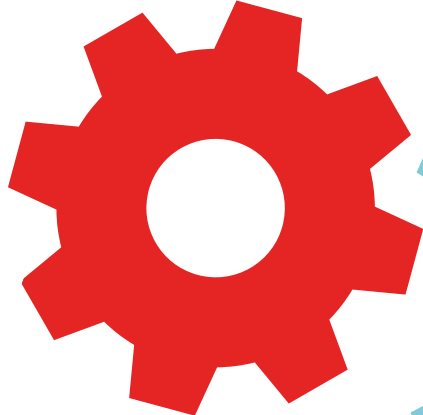
**IMAGE
PROCESSING**



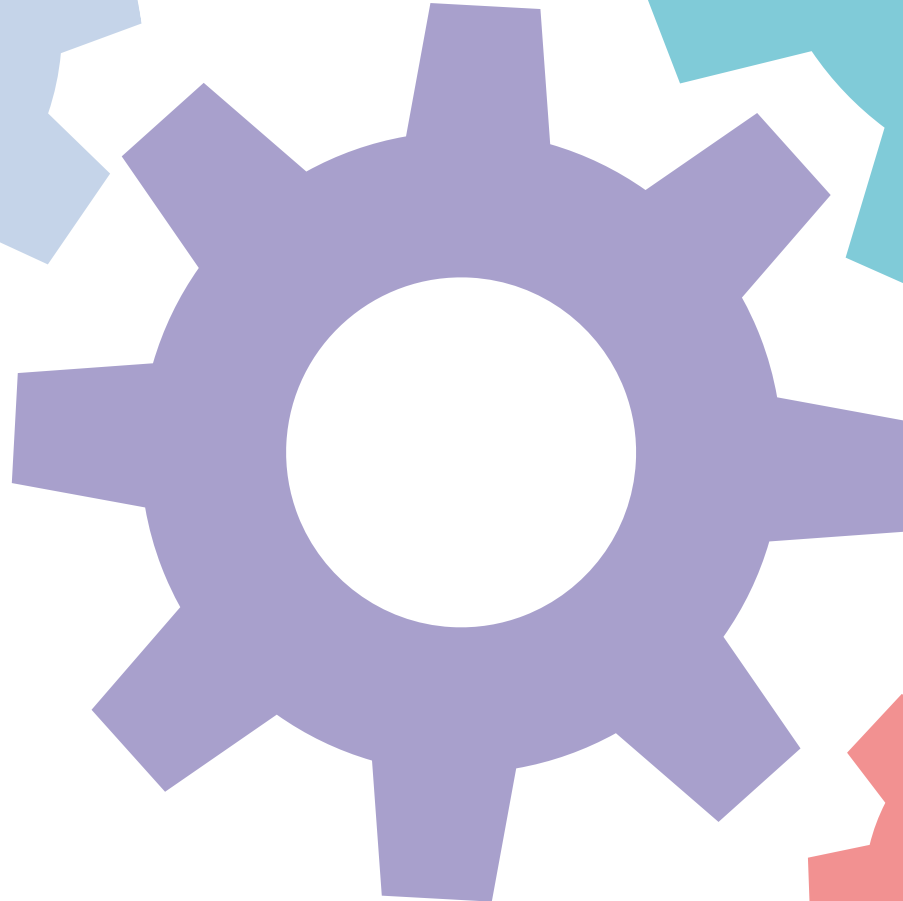
**PATIENT
MODELING**



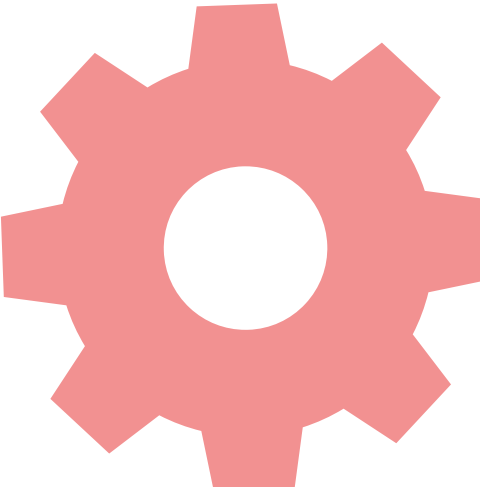
**ADVANCED
DOSIMETRIC MODELS**



**DOSIMETRIC
ANALYSIS**



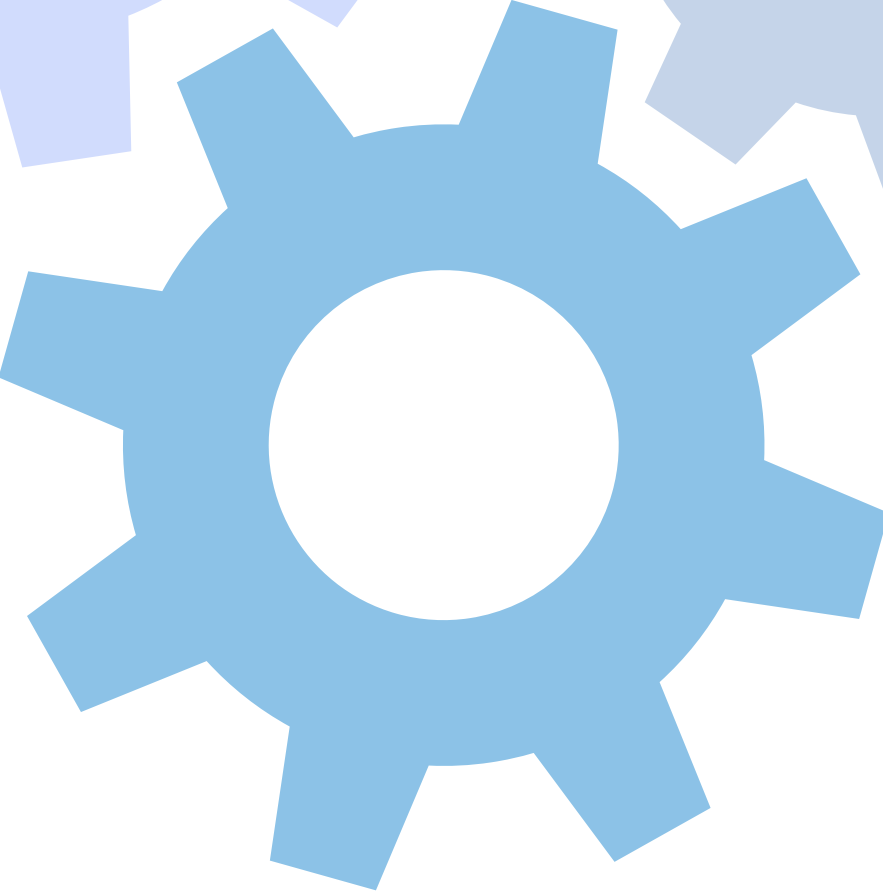
**MONTE CARLO
SIMULATIONS**



**AUTOMATIC
PATIENT
POSITIONING**

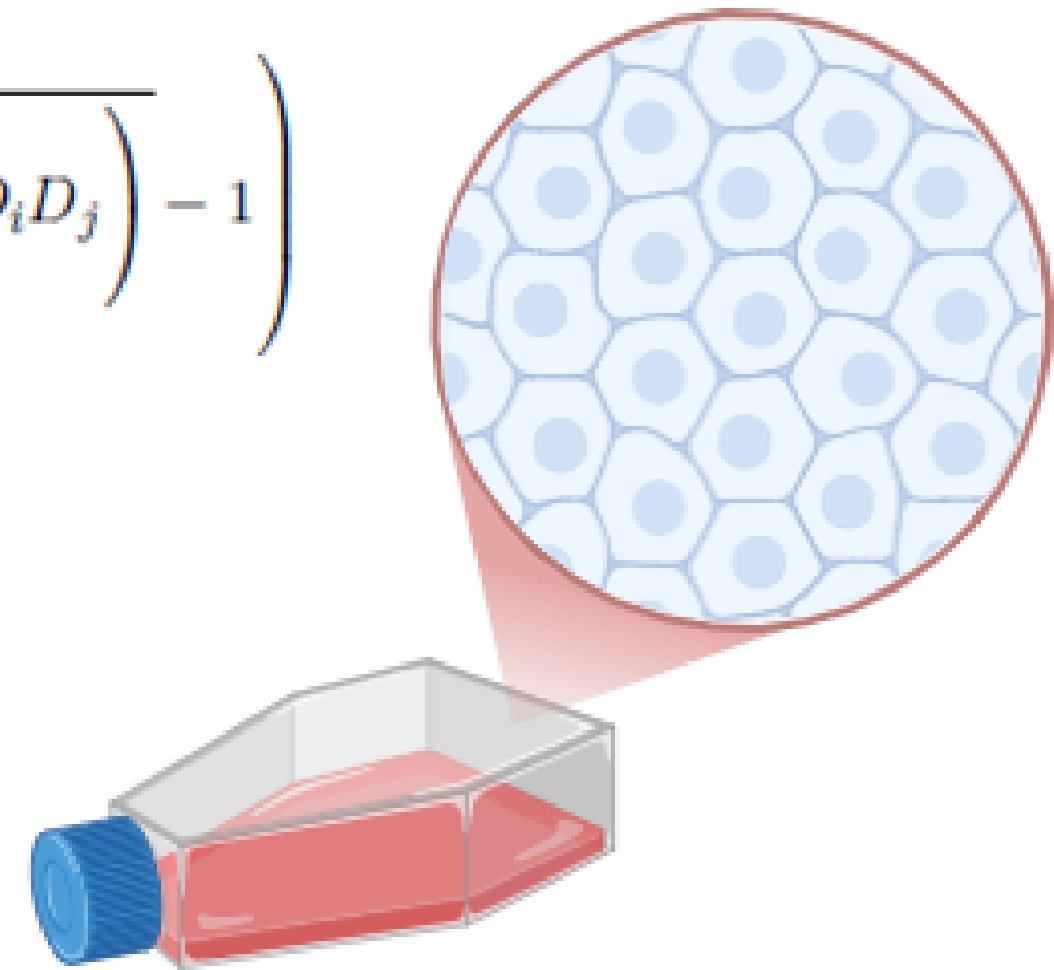
**AUTOMATIC
SEGMENTATION**

**REGION OF INTEREST
IDENTIFICATION**



Photon Isoeffective Dose Model

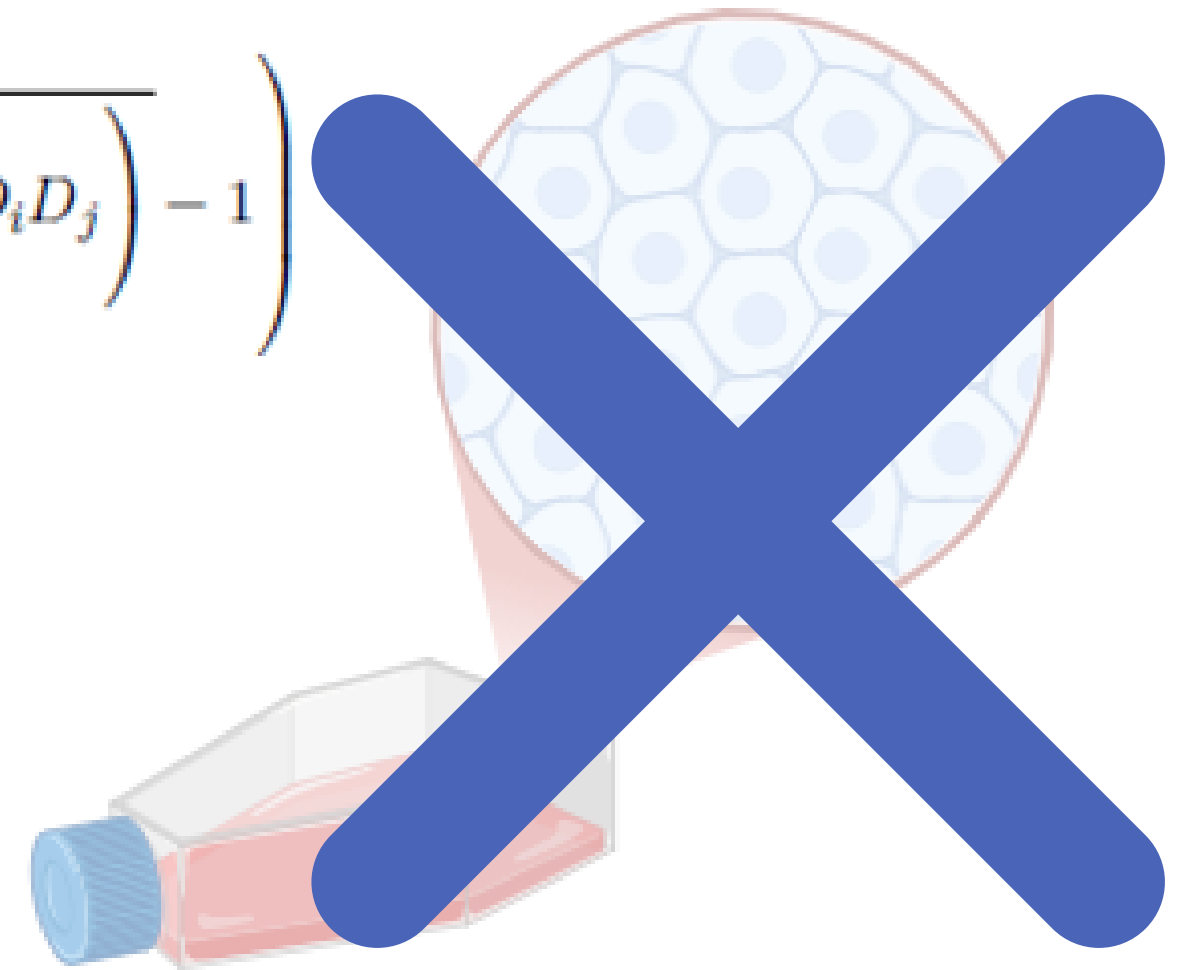
$$D_R(D_1, \dots, D_4) = \frac{1}{2} \frac{\left(\frac{\alpha}{\beta}\right)_R}{G_R} \times \left(\sqrt{1 + \frac{4G_R}{\alpha_R \left(\frac{\alpha}{\beta}\right)_R} \left(\sum_{i=1}^4 \alpha_i D_i + \sum_{i=1}^4 \sum_{j=1}^4 G_{ij}(\theta) \sqrt{\beta_i \beta_j} D_i D_j \right)} - 1 \right)$$



2D Cell Layers

Photon Isoeffective Dose Model

$$D_R(D_1, \dots, D_4) = \frac{1}{2} \frac{\left(\frac{\alpha}{\beta}\right)_R}{G_R} \times \left(\sqrt{1 + \frac{4G_R}{\alpha_R \left(\frac{\alpha}{\beta}\right)_R} \left(\sum_{i=1}^4 \alpha_i D_i + \sum_{i=1}^4 \sum_{j=1}^4 G_{ij}(\theta) \sqrt{\beta_i \beta_j} D_i D_j \right)} - 1 \right)$$



2D Cell Layers

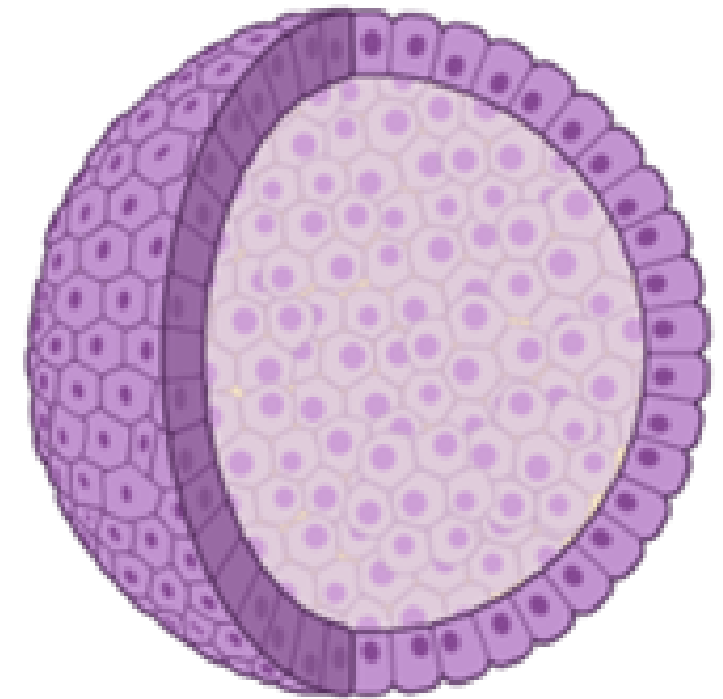
Photon Isoeffective Dose Model

$$D_R(D_1, \dots, D_4) = \frac{1}{2} \frac{\left(\frac{\alpha}{\beta}\right)_R}{G_R} \times \left(\sqrt{1 + \frac{4G_R}{\alpha_R \left(\frac{\alpha}{\beta}\right)_R} \left(\sum_{i=1}^4 \alpha_i D_i + \sum_{i=1}^4 \sum_{j=1}^4 G_{ij}(\theta) \sqrt{\beta_i \beta_j} D_i D_j \right)} - 1 \right)$$

Enhancement of the dosimetric model



Spheroids



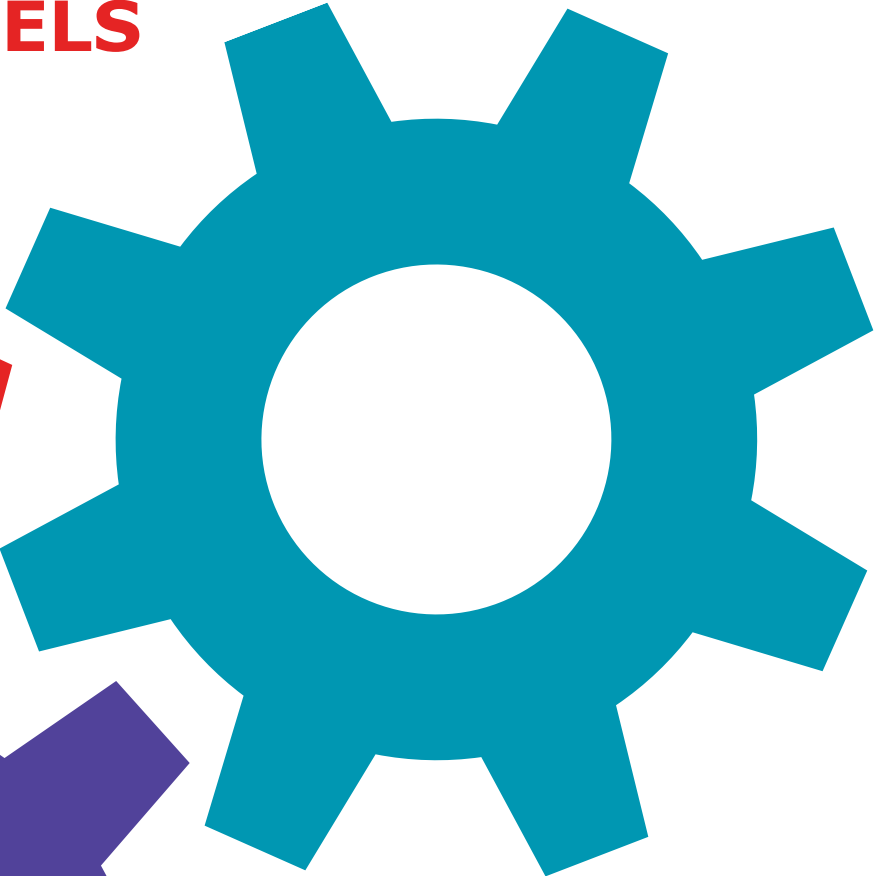
**IMAGE
PROCESSING**



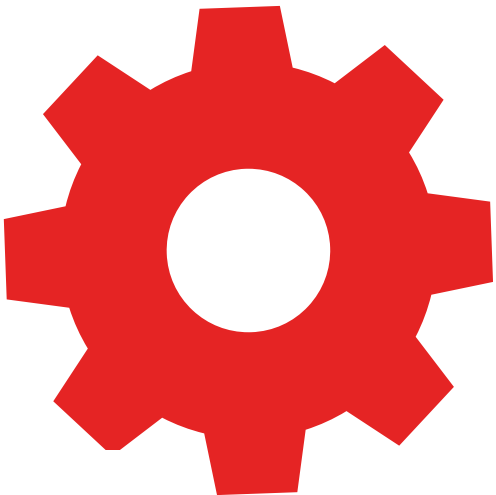
**PATIENT
MODELING**



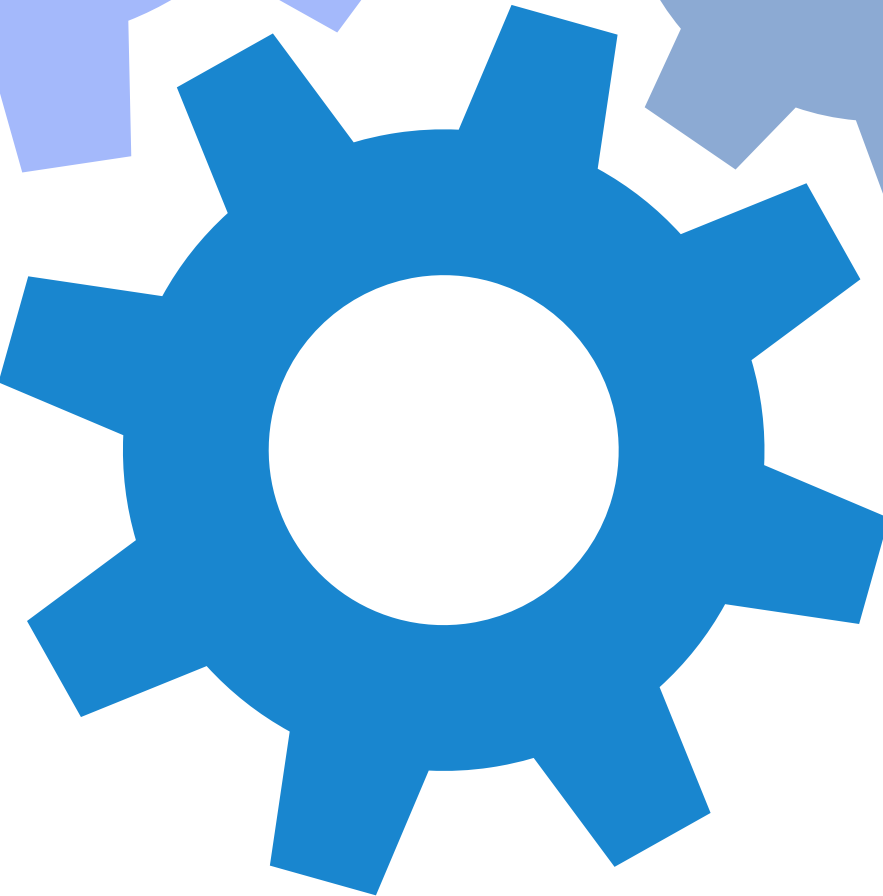
**ADVANCED
DOSIMETRIC MODELS**



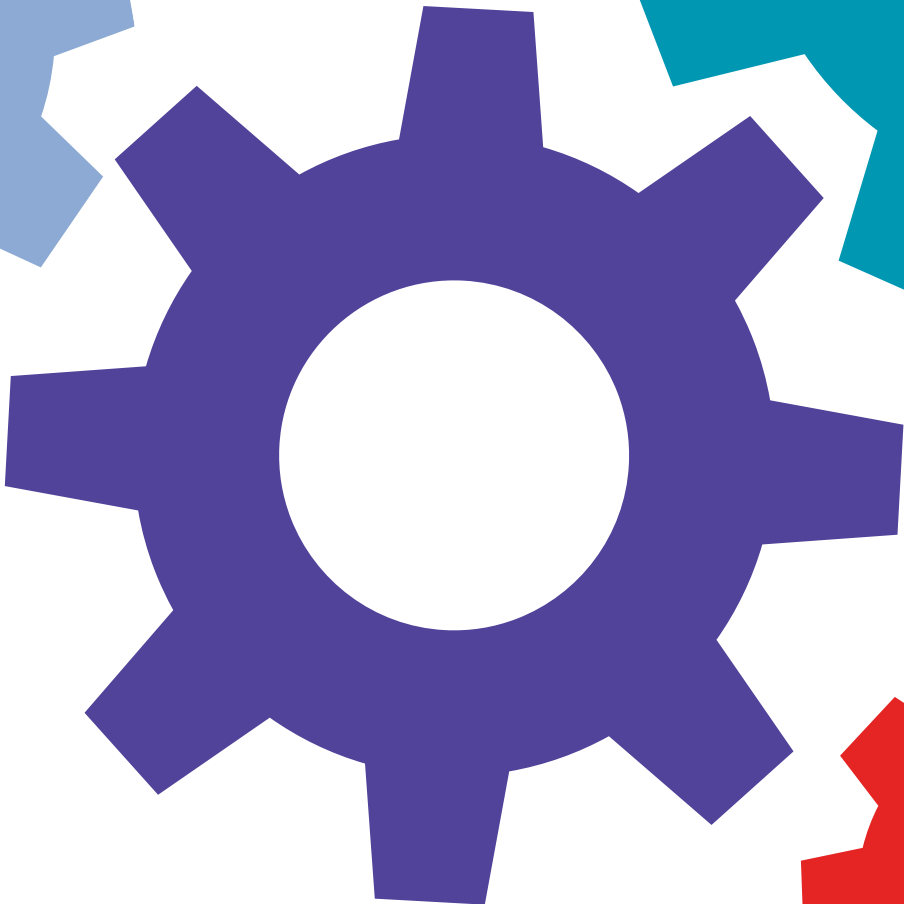
**DOSIMETRIC
ANALYSIS**



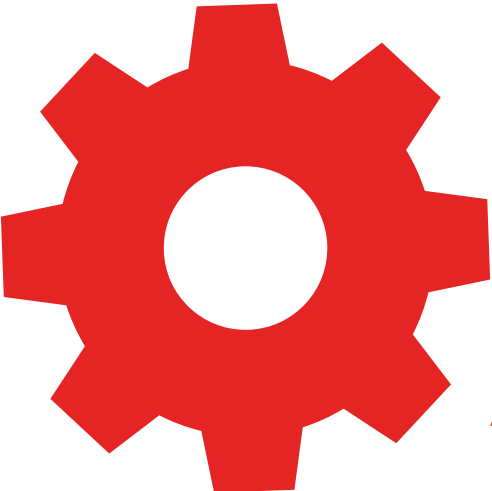
**AUTOMATIC
SEGMENTATION**



**REGION OF INTEREST
IDENTIFICATION**

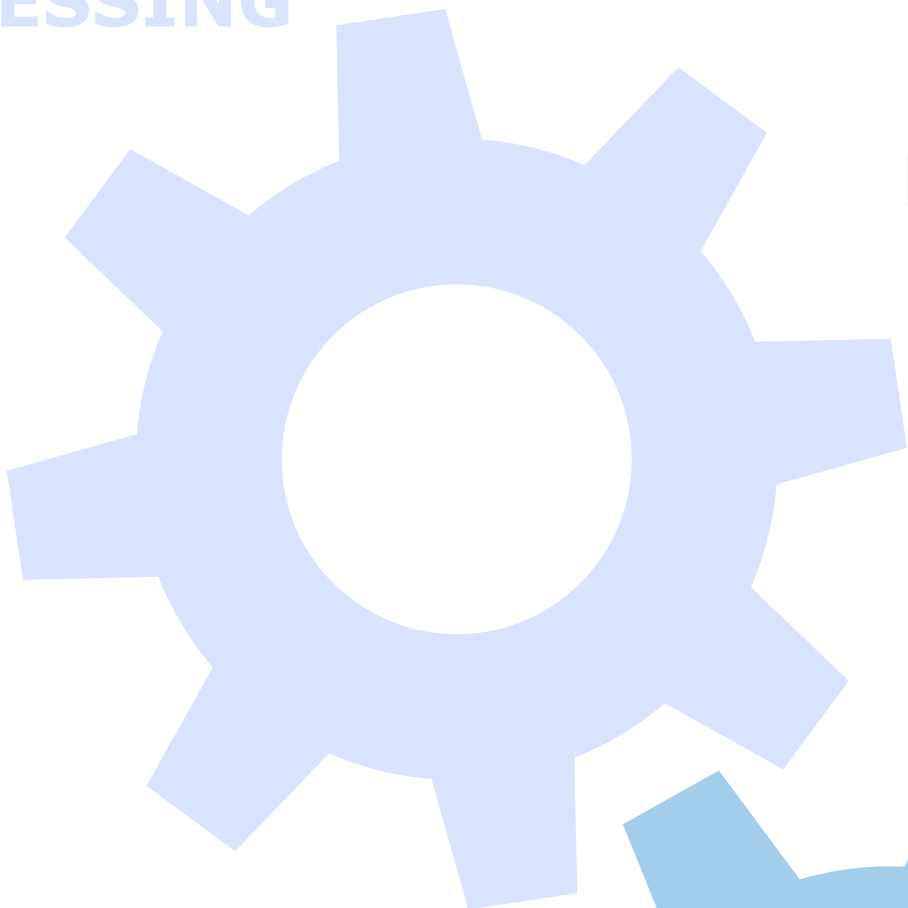


**MONTE CARLO
SIMULATIONS**



**AUTOMATIC
PATIENT
POSITIONING**

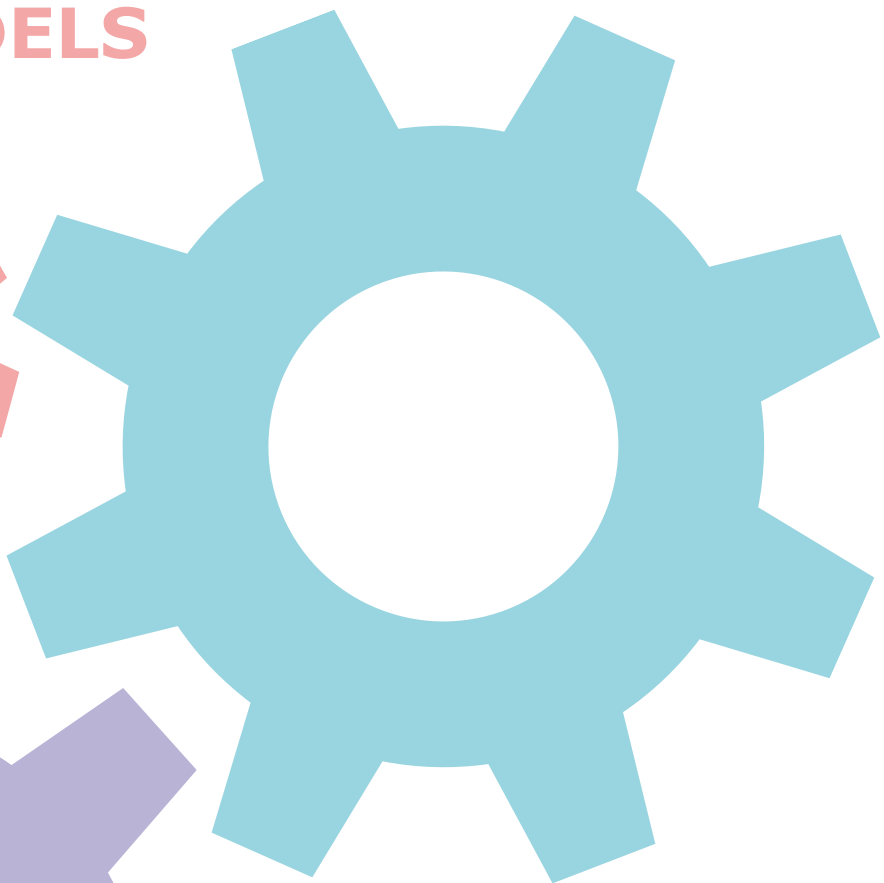
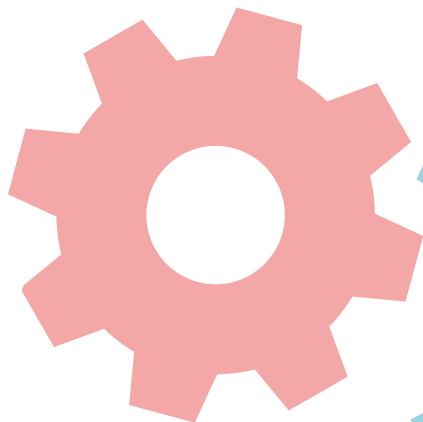
IMAGE
PROCESSING



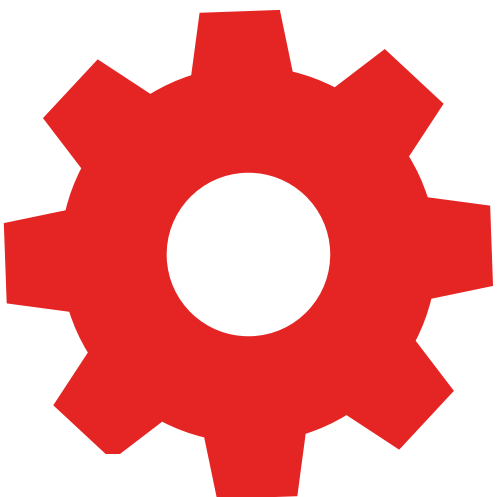
PATIENT
MODELING



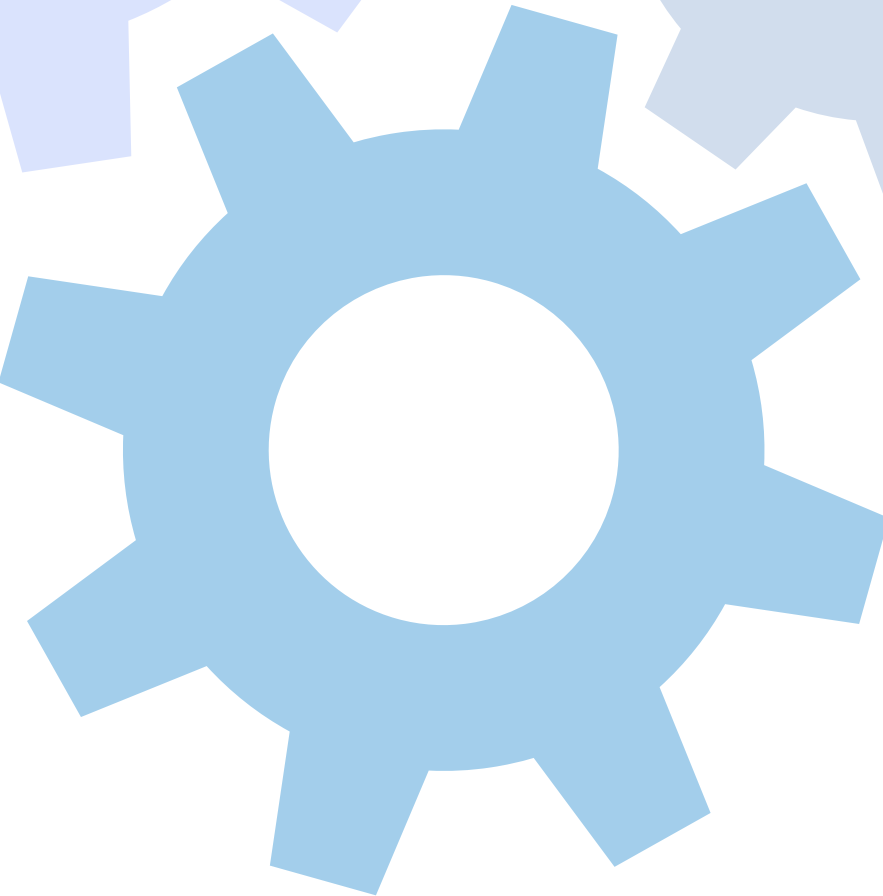
ADVANCED
DOSIMETRIC MODELS



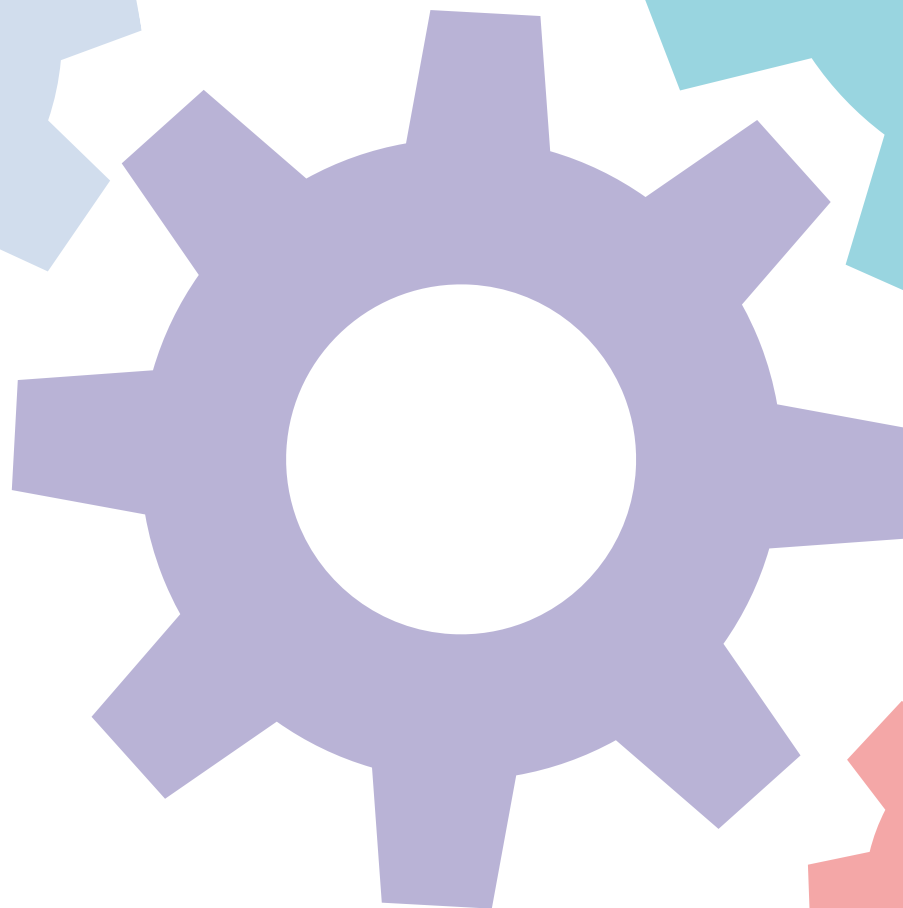
DOSIMETRIC
ANALYSIS



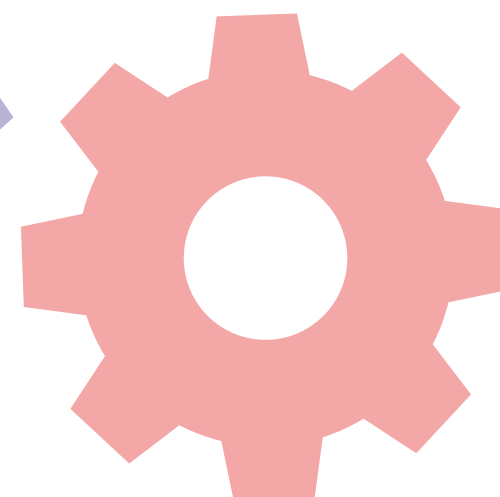
AUTOMATIC
SEGMENTATION



REGION OF INTEREST
IDENTIFICATION

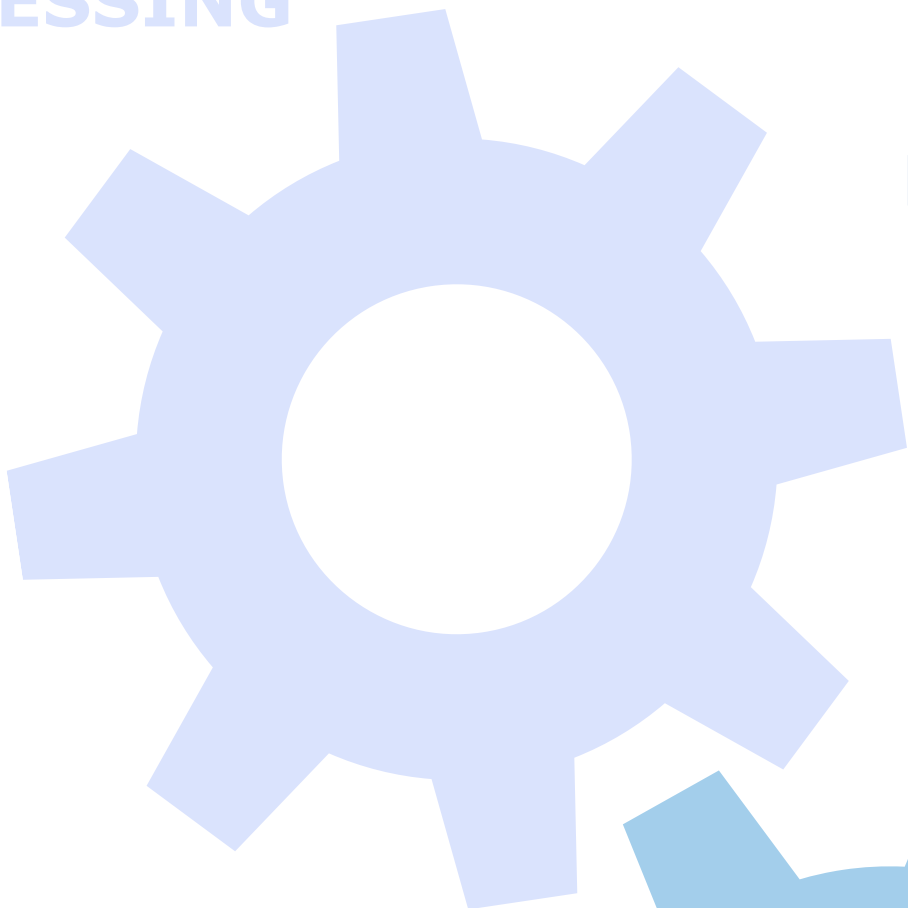


MONTE CARLO
SIMULATIONS



AUTOMATIC
PATIENT
POSITIONING

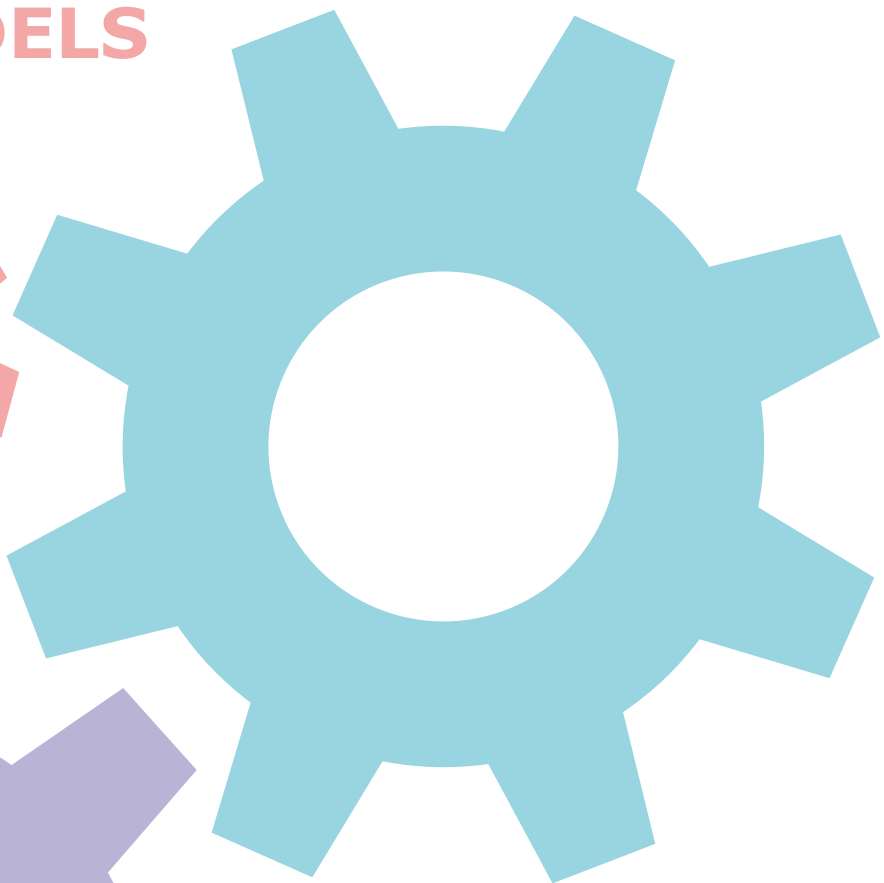
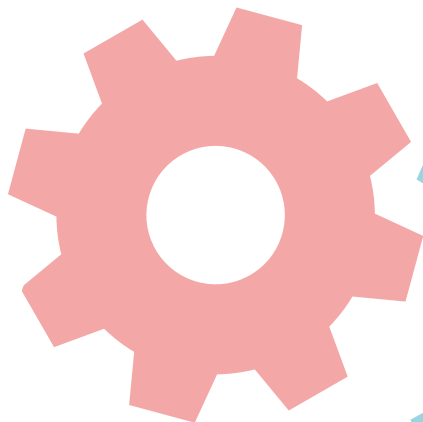
IMAGE
PROCESSING



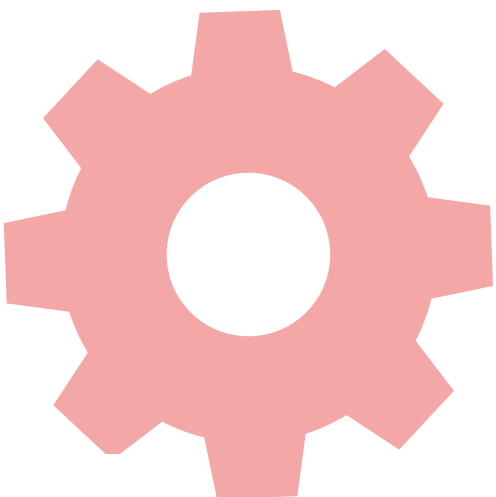
PATIENT
MODELING



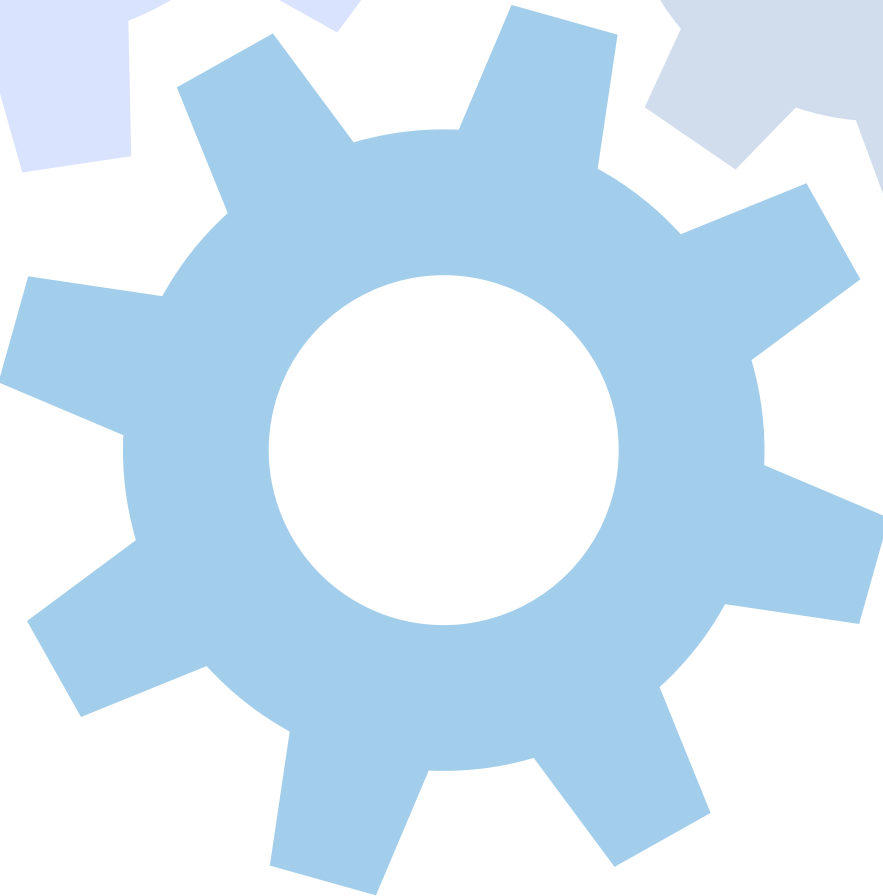
ADVANCED
DOSIMETRIC MODELS



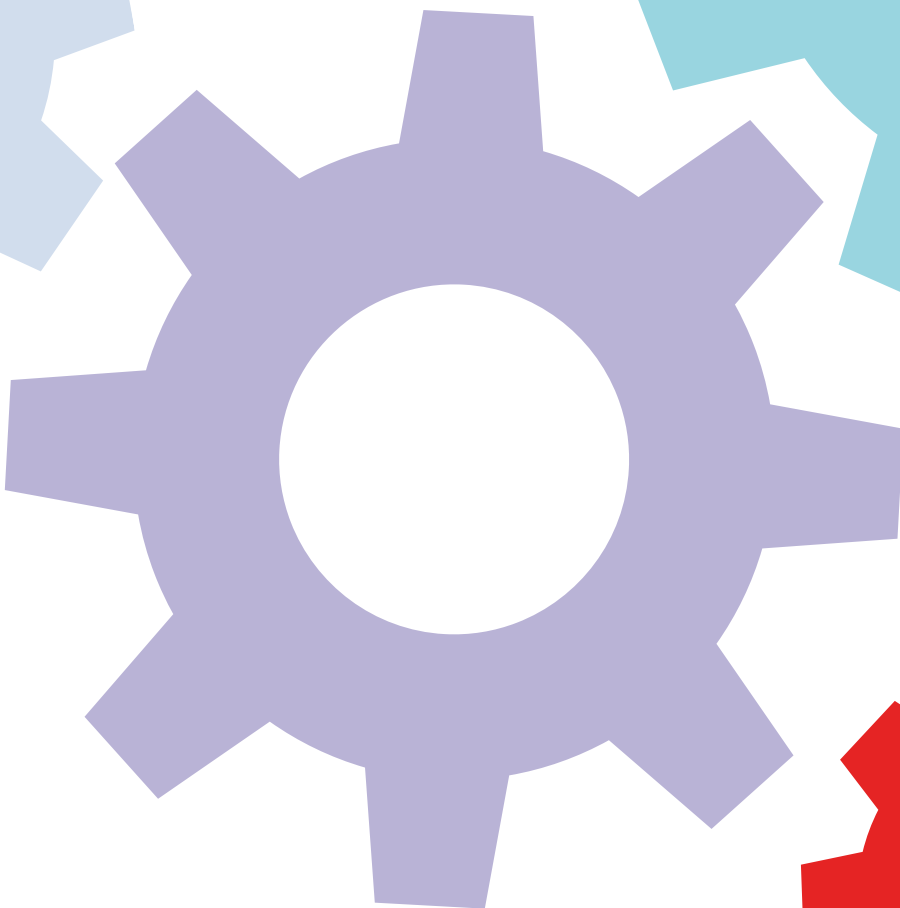
DOSIMETRIC
ANALYSIS



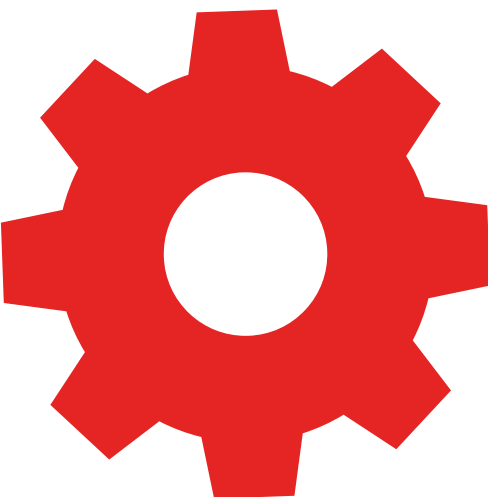
AUTOMATIC
SEGMENTATION



REGION OF INTEREST
IDENTIFICATION

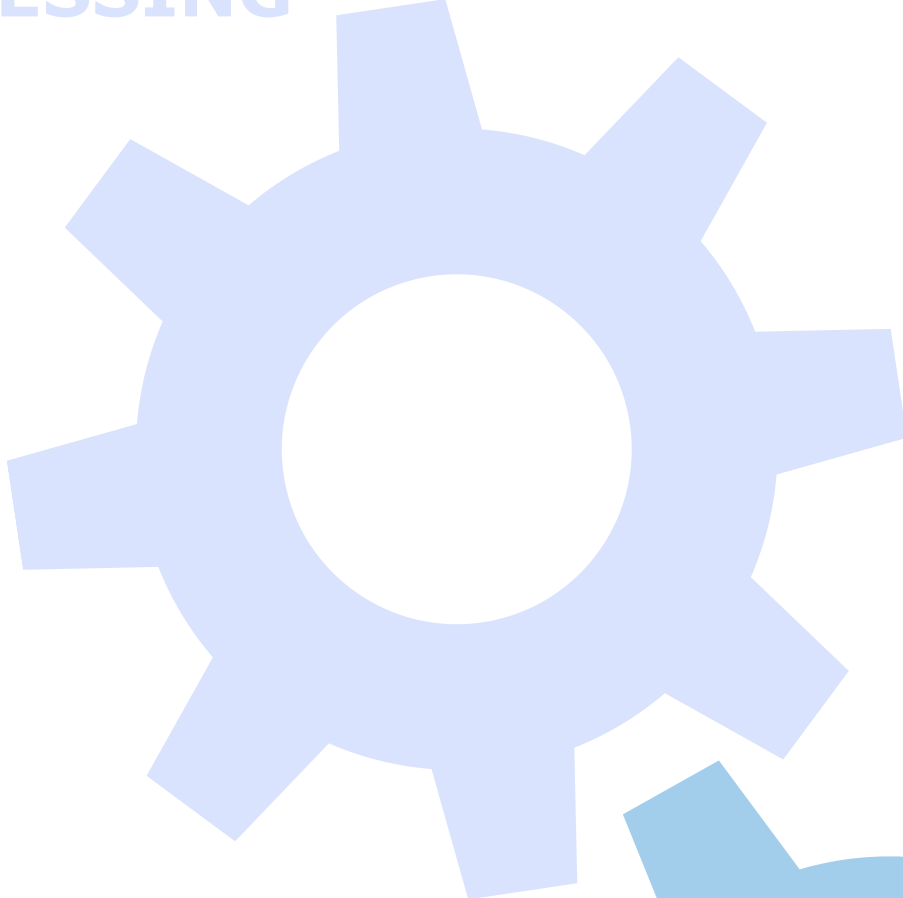


MONTE CARLO
SIMULATIONS



AUTOMATIC
PATIENT
POSITIONING

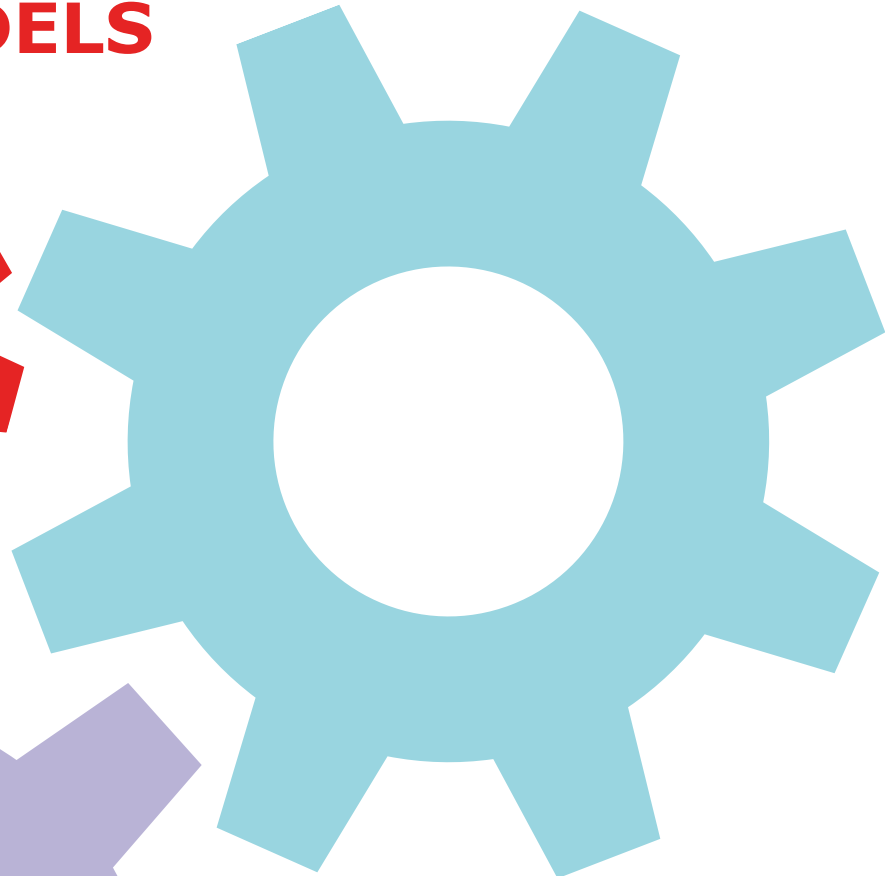
**IMAGE
PROCESSING**



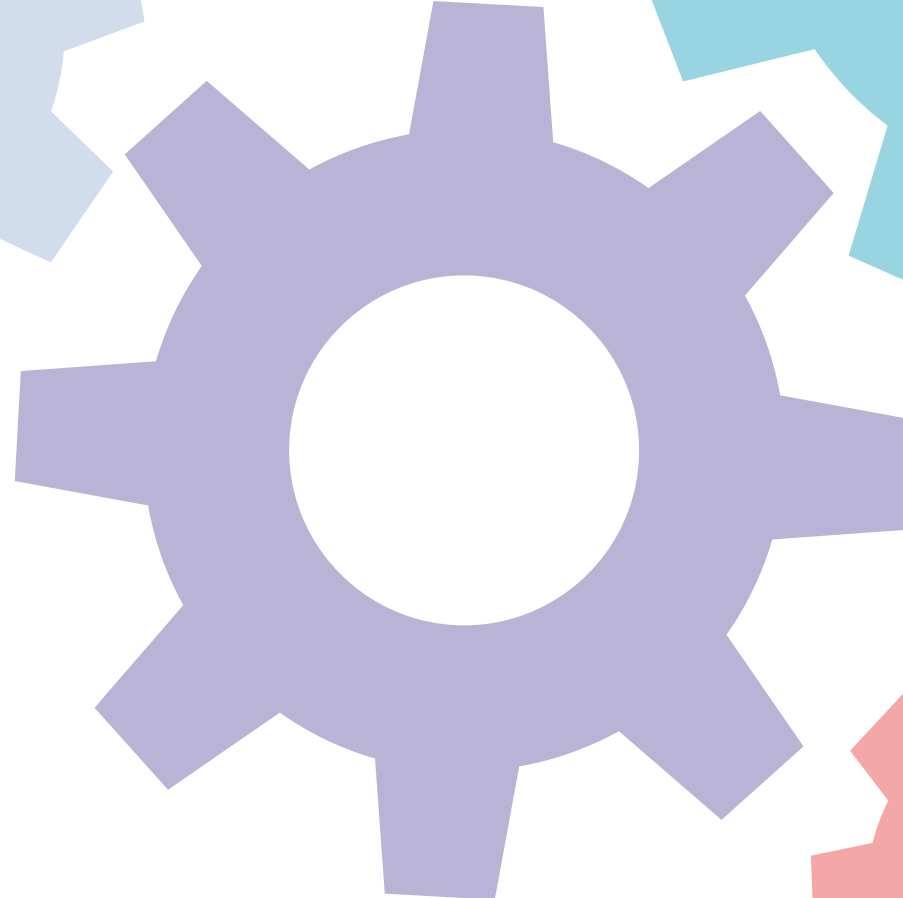
**PATIENT
MODELING**



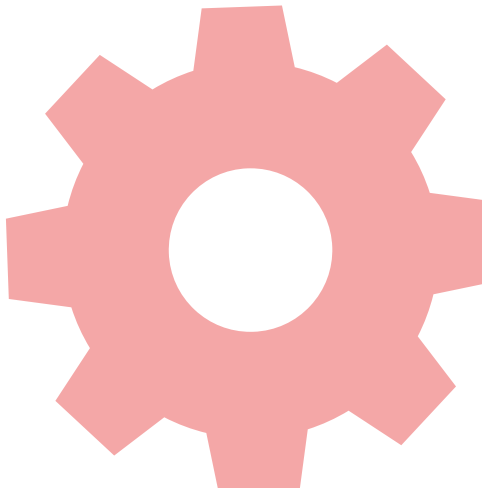
**ADVANCED
DOSIMETRIC MODELS**



**DOSIMETRIC
ANALYSIS**



**MONTE CARLO
SIMULATIONS**



**AUTOMATIC
PATIENT
POSITIONING**

**AUTOMATIC
SEGMENTATION**

**REGION OF INTEREST
IDENTIFICATION**

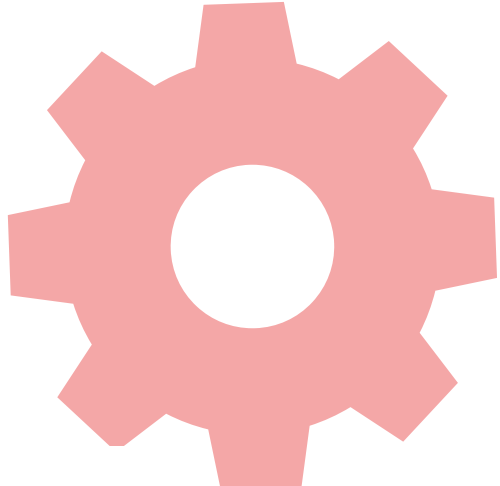
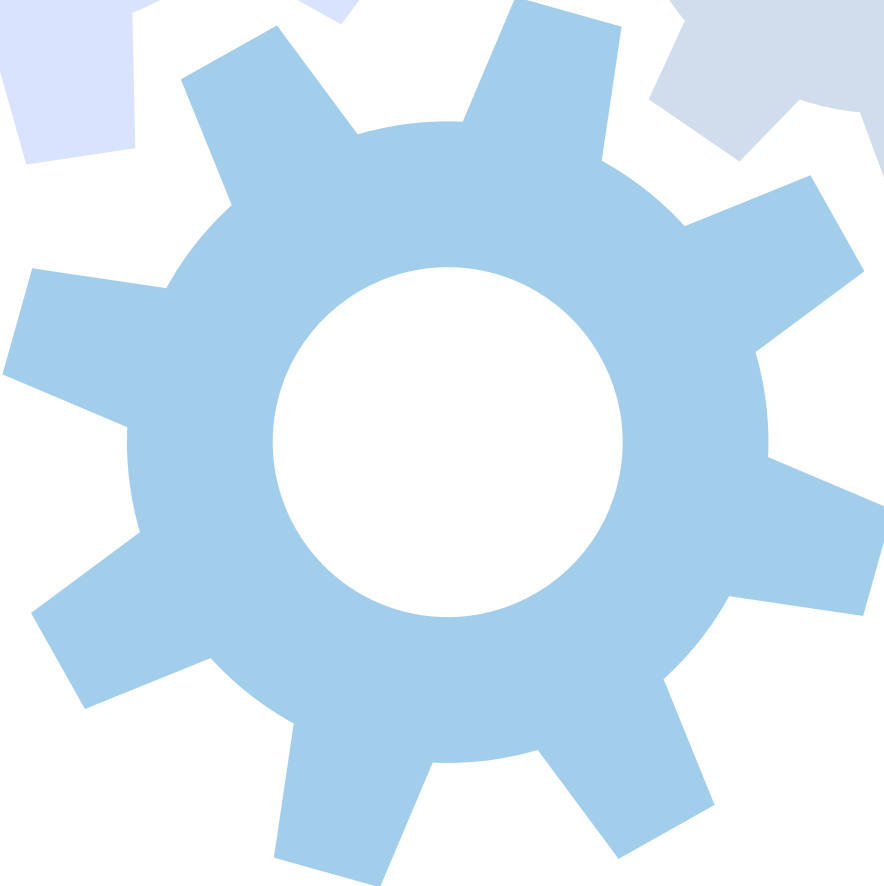


IMAGE
PROCESSING

ADVANCED
DOSIMETRIC MODELS

PATIENT
MODELING

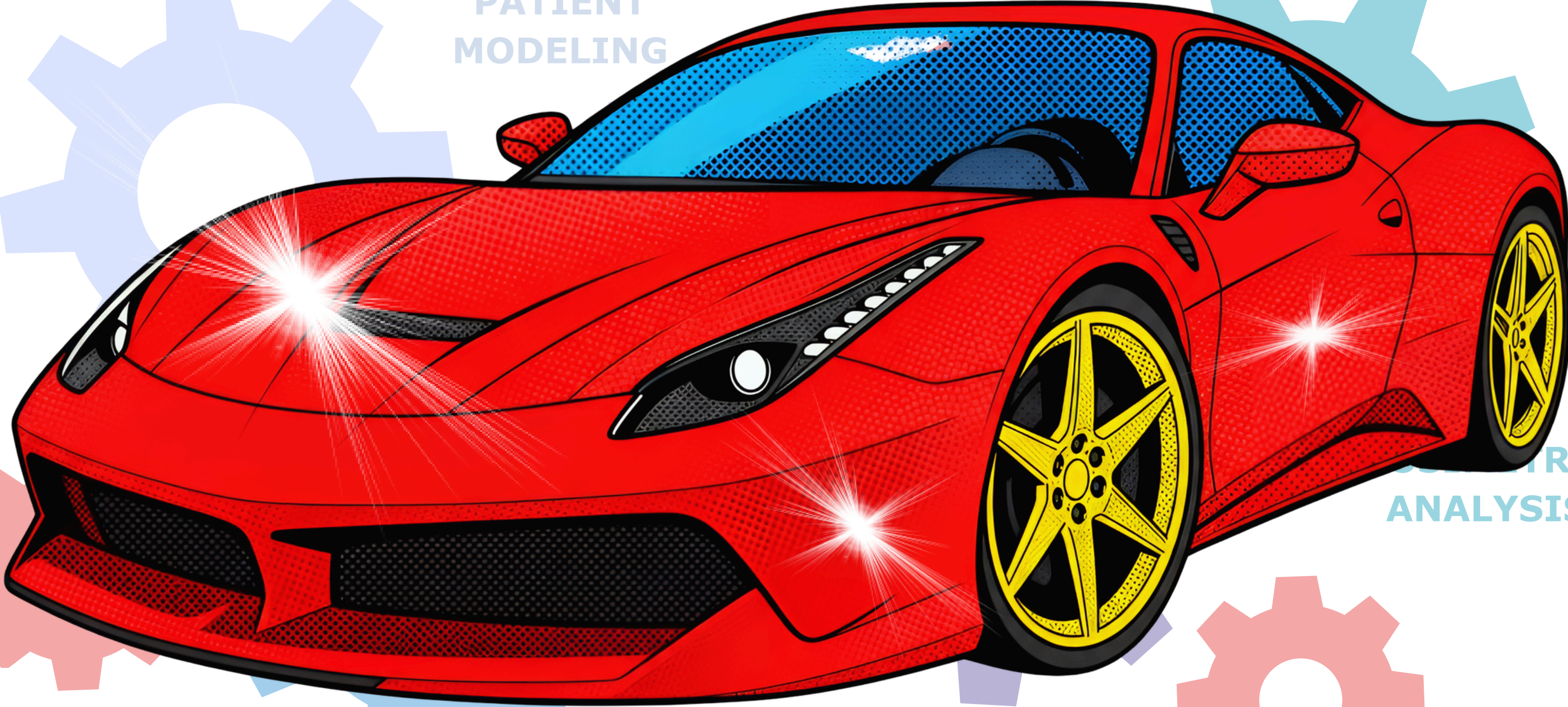
DOSIMETRIC
ANALYSIS

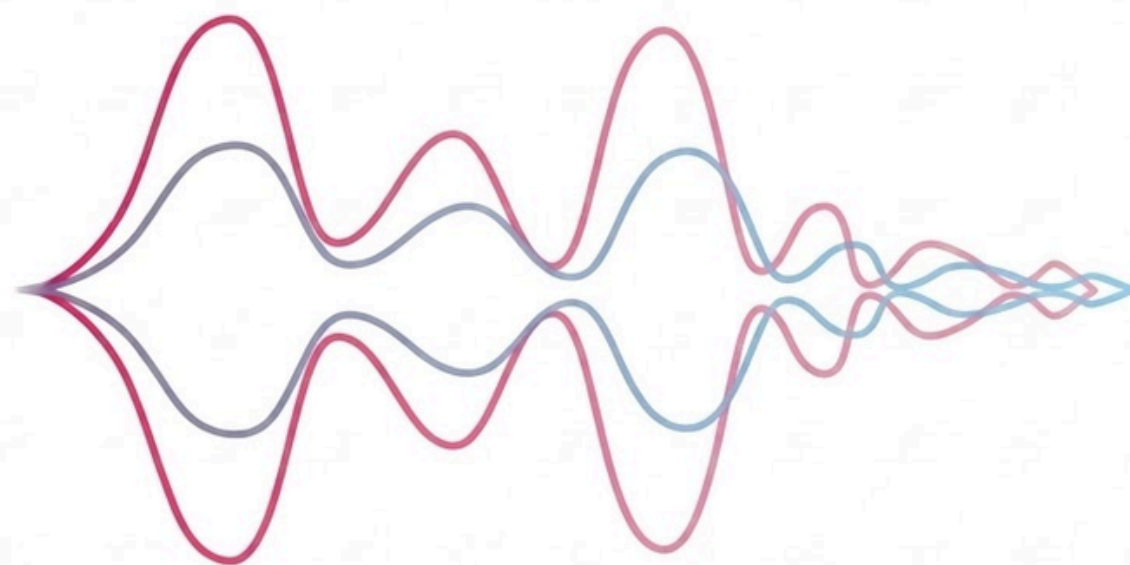
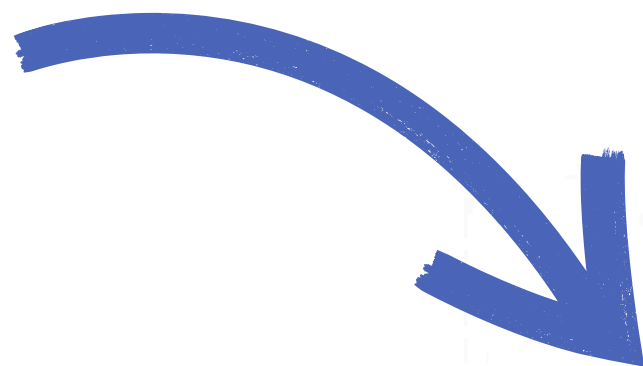
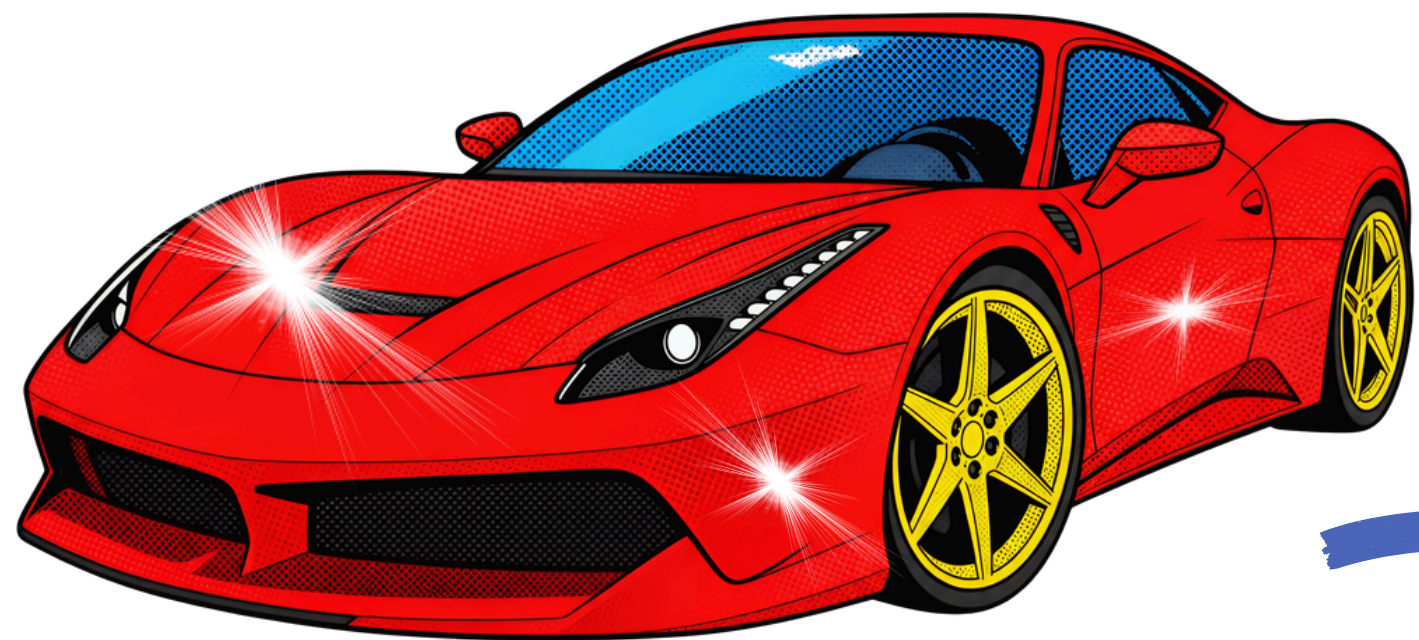
AUTOMATIC
SEGMENTATION

REGION OF INTEREST
IDENTIFICATION

MONTE CARLO
SIMULATIONS

AUTOMATIC
PATIENT
POSITIONING



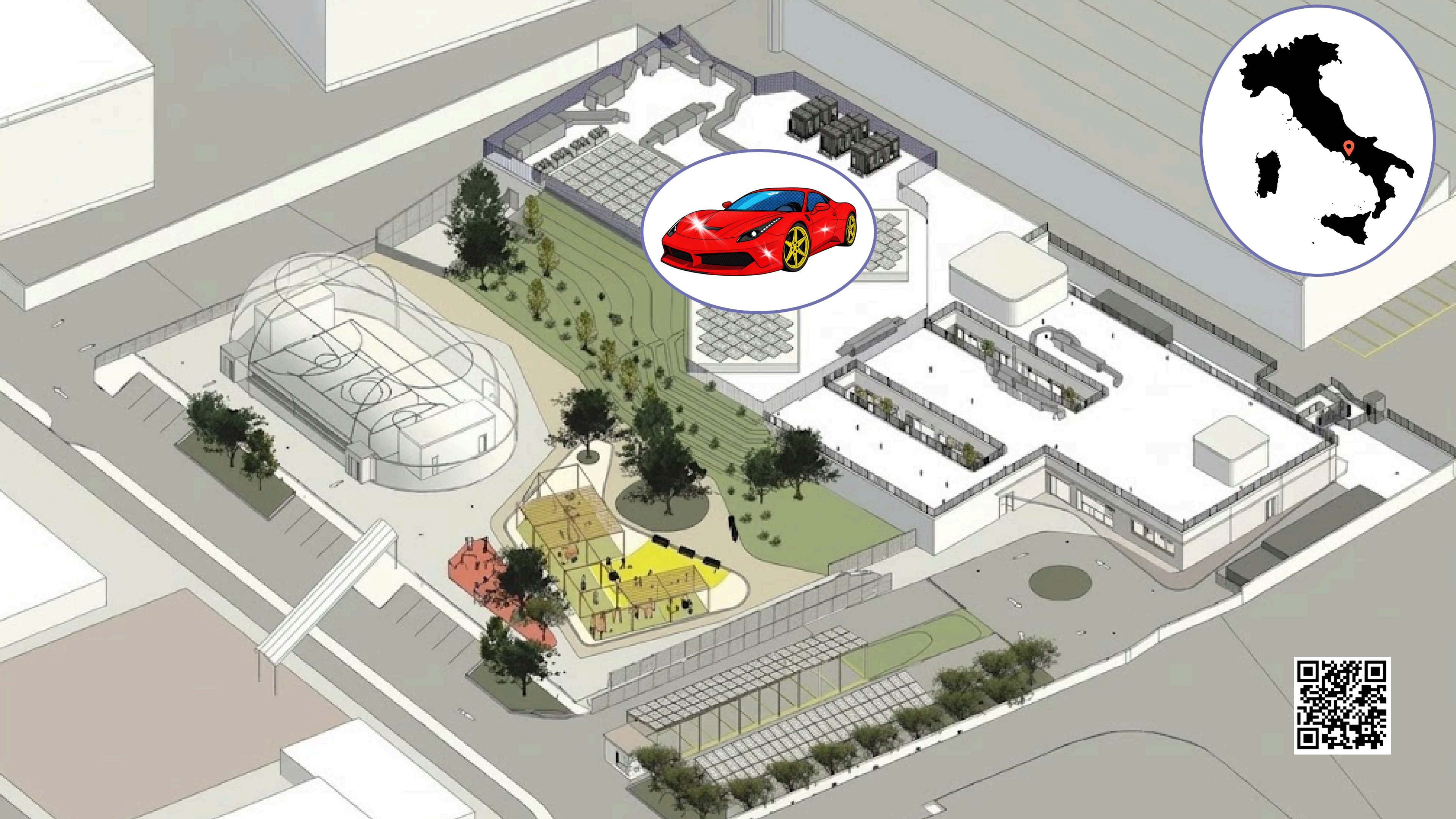


Anthem

AdvaNced Technologies for Human-centEred Medicine







Feseability & Collaborations

Experimental Activities

Neutron irradiation facility @TRIGA Mark II reactor and fully equipped biology laboratories

International Collaborations

INFN projects (AI_MIGHT and IT_STARTS) and international collaborations (Argentina, China, Taiwan, France, Finland, Spain groups)



Research Products



Teaching seminars for the class of Experimental Physics for the course in the Biotechnology undergraduate program at the University of Pavia (A.A. 2025-2026).

Teaching seminars for the class of Physical Sensors and Systems for Biomedical Imaging for course in the Physics undergraduate program at the University of Pavia (A.A. 2024-2025, 2025-2026).

Tutoring activity for the course Fundamentals of Physics - Mechanics within the Blended E-learning Tutoring Programme, for first-semester courses of the Inter-University Bachelor's Degree Programme in Physical Sciences for Innovative Technologies (A.A. 2025-2026).

Tutoring activity for the course Adeguamento delle conoscenze fisicomatematiche di base per il conseguimento degli obiettivi didattici attinenti l'area didatticoformativa di fisica e fisica medica for the first-semester course in the Medicine undergraduate program at the University of Pavia (A.A. 2025-2026)



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G. Garini, C. Magni, I. Postuma, S. Fatemi, R. L. Ramos, B. Marcaccio, C. Pezzi, L. Bagnale, S. Sandri, G. De Matteis, G. Paolisso, V. Vercesi and S. Bortolussi, ***Radiation protection assessment of patient activation and dosimetry in Boron Neutron Capture Therapy***, Rad Phys and Chem 237, 2025, 112900.

B. Marcaccio, A. Portu, G. Santa Cruz, L. Cansolino, C. Ferrari, C. Pezzi, S. Fatemi, I. Postuma, S. Bortolussi, S. Gonzalez, ***Unraveling the role of boron microdistribution in BNCT dosimetry of Glioblastoma Multiforme: combined theoretical and experimental insights***, Phys. Med. Biol 71, 2026.

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C. Pezzi, F. Morosato, B. Marcaccio, L. Bagnale, S. Bortolussi, R. L. Ramos, V. Vercesi, I. Postuma, S. Fatemi, ***From segmentation to positioning: How an AI-based TPS can optimize BNCT for glioblastoma multiforme treatment***, Il Nuovo Cimento C, 49, 2026, Article 199.



Co-supervisor for the BSc thesis in Physics at University of Pavia of Andrea Gastaldi (A.A. 2025-2026).

Co-supervisor for the MSc thesis in Physical Engineering at Polytechnic of Milan of Alessandra Catania (A.A. 2025-2026).

Co-supervisor for the MSc thesis in Physics at University of Pavia of Emilia Dottorini (A.A. 2025-2026).

