Monte Carlo Interface to matRad for Proton Dose Calculations

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German Cancer Research Center (DKFZ)

On behalf of the matRad development team

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6th Annual Loma Linda Workshop

Outline

- What is matRad?
- Monte Carlo interface to matRad
- Examples of Monte Carlo applications in matRad

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What is matRad?

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Treatment Planning

- Computerized process
- Dose is numerically simulated and optimized

Commercial solutions are closed systems (Black Box)	⚡	Research needs flexible, accessible software

Examples for current projects at dkfz:

- Biological Optimization

  (RBE, effect, mixed-modality)
- Probabilistic dose calculation & optimization

=> low-level access to dose calculation / optimization needed

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What is matRad?

matRad
www.matrad.org

- Toolkit for three-dimensional **intensity-modulated** treatment planning for **photons, protons and carbon ions**
- matRad implements well-established radiotherapy algorithms for **research & education**

Why?

Supporting open science, reproducibility and education

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What is matRad?

Properties:

- **Open-source code, patients and machine files on GitHub**
- **Graphical user interface available**
- **Non-linear constrained dose optimization (IPOPT)**
- **Import & export functionalities (DICOM, binary formats)**
- **Entirely written in Matlab and compatible with GNU Octave**

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Development and Cooperation

GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION

Deutsche Forschungsgemeinschaft

BA 2279/3-1

Heidelberger Ionenstrahl-Therapiezentrum

Development team @ dkfz

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***Contributors to the MC interface for protons**

HIT cooperation

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Hubert Gabrys
Silke Ulrich
Oliver Schrenk
Ahmad Neishabouri

Advisors

Martin Siggel
Peter Ziegenhein

matRad is already adopted at more than 25 institutes worldwide

University of Central Florida

Clínica El Rosario
Amor que Acompaña y Servicio que Alivia

Carleton University
Canada's Capital University

HIT Heidelberger Ionenstrahl-Therapiezentrum

Pontificia Universidad Católica de Chile

Canberra Hospital and Health Services

University of Zurich UZH

Universität Heidelberg
Zukunft seit 1386

University of Oxford

Technical University of Munich TUM

University of Kentucky

The University of Western Australia

Current Release “Blaise” 2.10.0

- 3D dose calculation (validated)

  Photons: SVD pencil-beam algorithm + sequencing
  MC interface to ompMC (open source)

  Protons: Pencil-Beam algorithm + const. RBE
  MC interface to MCsquare (open source)

  Carbon ions: Pencil-Beam algorithm + biol. effect / RBE

- Base data

  Patient data (CORT data set) & DICOM Import

  Physical (& biological) base data for photon LINAC as well as a proton and a carbon-ion machine

- Inverse planning with new optimization interface

  Photons: Physical dose optimization & DAO

  Protons: + Constant RBE optimization

  Carbon-ions: + RBE (variable) or effect optimization

- Scripting & Graphical User Interface

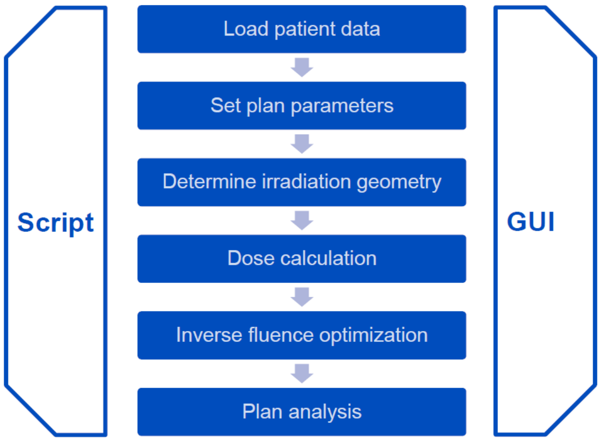

MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

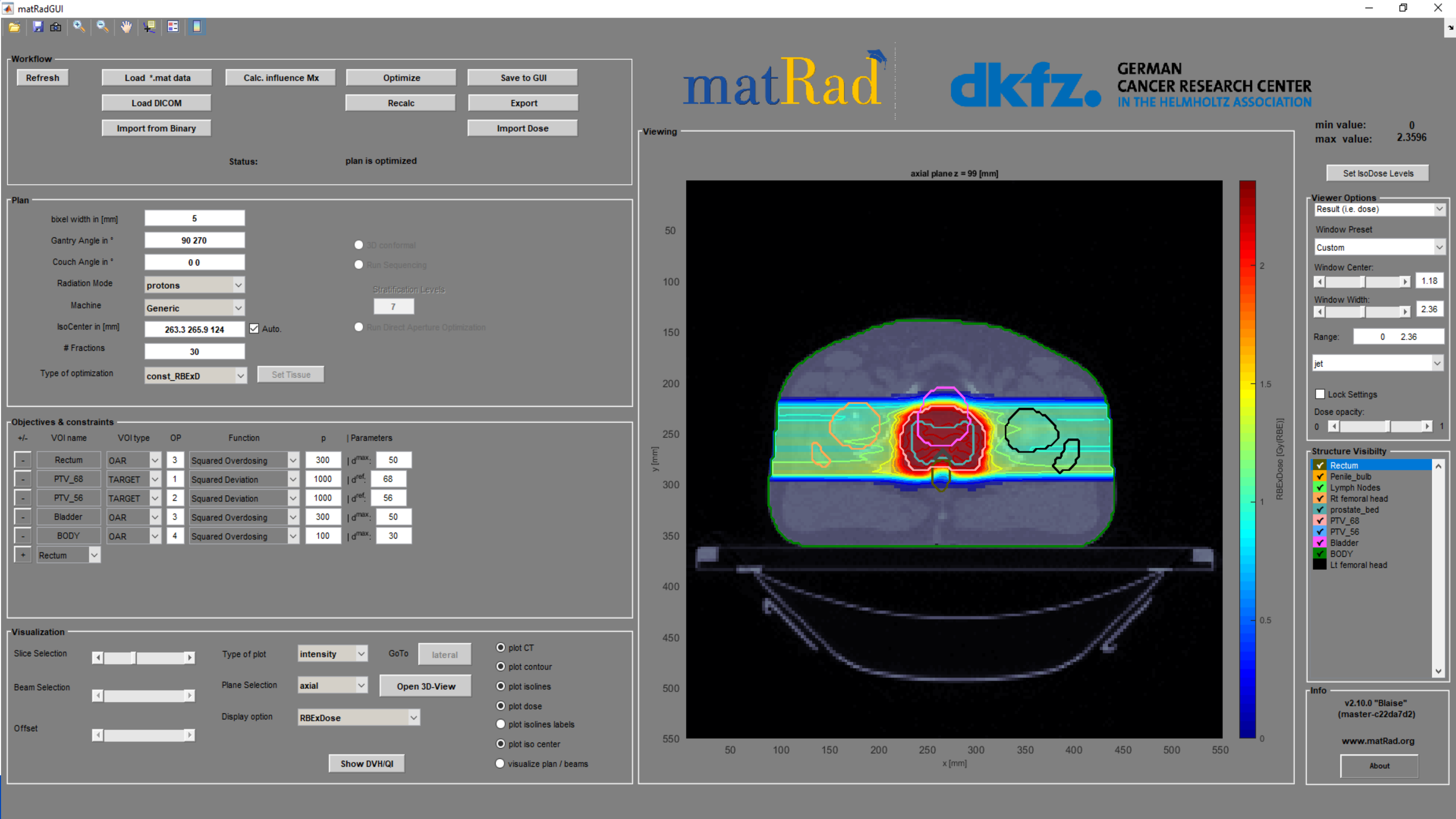
Research Article | Open Access

Development of the open-source dose calculation and optimization toolkit matRad

Hans-Peter Wieser, Eduardo Cisternas, Niklas Wahl, Silke Ulrich, Alexander Stadler, Henning Mescher, Lucas-Raphael Müller, Thomas Klinge, Hubert Gabrys, Lucas Burigo, Andrea Mairani, Swantje Ecker, Benjamin Ackermann, Malte Ellerbrock, Katia Parodi, Oliver Jäkel, Mark Bangert

Wieser et al., 2017, Med Phys 44(6)
- among top 20 downloaded Med Phys papers in 2017 -




matRadGUI
Workflow
Refresh
Load *.mat data
Calc. influence Mx
Optimize
Save to GUI
Load DICOM
Recalc
Export
Import from Binary
Import Dose
Status:
plan is optimized
matRad
dkfz.
GERMAN
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Plan
bixel width in [mm]
5
Gantry Angle in °
90 270
Couch Angle in °
0 0
Radiation Mode
protons
Machine
Generic
IsoCenter in [mm]
263.3 265.9 124
Auto.
Fractions
30
Type of optimization
const_RBExD
Set Tissue
3D conformal
Run Sequencing
Stratification Levels
7
Run Direct Aperture Optimization
Objectives & constraints
+/-
VOI name
VOI type
OP
Function
p
Parameters
Rectum
OAR
3
Squared Overdosing
300
50
PTV_68
TARGET
1
Squared Deviation
1000
68
PTV_56
TARGET
2
Squared Deviation
1000
56
Bladder
OAR
3
Squared Overdosing
300
50
BODY
OAR
4
Squared Overdosing
100
30
Rectum
Visualization
Slice Selection
Beam Selection
Offset
Type of plot
intensity
GoTo
lateral
Plane Selection
axial
Open 3D-View
Display option
RBExDose
Show DVH/QI
plot CT
plot contour
plot isolines
plot dose
plot isolines labels
plot iso center
visualize plan / beams
Viewing
axial plane z = 99 [mm]
y [mm]
x [mm]
RBExDose [Gy(RBE)]
min value: 0
max value: 2.3596
Set IsoDose Levels
Viewer Options
Result (i.e. dose)
Window Preset
Custom
Window Center:
1.18
Window Width:
2.36
Range:
0 2.36
jet
Lock Settings
Dose opacity:
Structure Visibilty
Rectum
Penile_bulb
Lymph Nodes
Rt femoral head
prostate_bed
PTV_68
PTV_56
Bladder
BODY
Lt femoral head
Info
v2.10.0 "Blaise"
(master-c22da7d2)
www.matRad.org
About

Monte Carlo interface to matRad
(for protons and ion beams)

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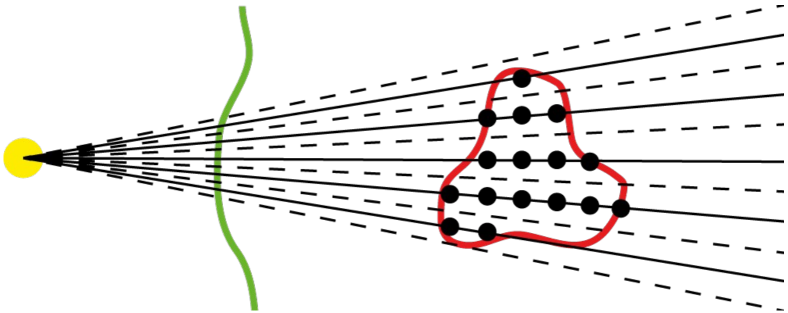
IMPT planning in matRad

Ray casting => Definition of pencil beams



1 Determine irradiation geometry

2 Ray casting is used to defined the radiological depth of the target volume.

3 Definition of pencil beam parameters (scanning positions and beam energy) is defined w.r.t. the radiological depth

4 Dose influence matrix (D_{ij}) is calculated using pencil beam algorithm (alternatively using Monte Carlo)

5 IMPT optimization is performed.

6 (Optionally) Forward recalculation of plan is performed with Monte Carlo.

$$D_{ij}$$

Inverse plan optimization

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Pipeline with MC interface

matRad

MATLAB

- Generate plan settings
- Export CT
- Define MC simulation settings

MC code

- Simulate plan

MATLAB

- Extract MC results
- Transform data
- Pipeline completed

The pipeline can be used to:

1. Recalculate the IMPT plan

2. Compute the influence matrix (MC-based treatment planning)

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Currently supported MC codes for protons and ion-beams

Protons only

Souris K, Lee JA, Sterpin E.
Fast multipurpose Monte Carlo simulation for proton therapy using multi- and many-core CPU architectures, Med Phys. 2016.
http://www.openmcsquare.org/

Protons and ion beams

Perl J, Shin J, Schumann J, Faddegon B, Paganetti H.
TOPAS: an innovative proton Monte Carlo platform for research and clinical applications. Med Phys. 2012 Nov; 39(11):6818-37
http://www.topasmc.org/

Beam Source Definition – Machine Base Data

The beam source parameters are defined in the **machine base data** including the **nominal beam energies**, **range in water**, and **spot size**.

In addition, further machine parameters should be specified including the **SAD** and **nozzle to axis distance**.

The MC proton beam is defined as an **emittance source** with the **beam optics** depending on the beam energy and X and Y scanning direction.

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The MC interface explores the MCsquare built-in capabilities to:

- convert patient HU to material
- load PBS plan information

The CT data is exported in the ITK MetaImage Header (MHD) format.

A plain text file with the PBS plan definition (gantry and couch angles, energy layers, spot positions and current) is exported following the MCsquare format.

matRad initiate the MC simulation and resume control at the end of MCsquare execution to extract the results written in MHD format.

matRad + TOPAS

The MC interface explores the TOPAS built-in capabilities to:
- convert patient HU to material
- define multiple scoring quantities in the CT geometry

No built-in functionality to read PBS plan information. → Scanning direction, energy, current and beam optics for each pencil beam are dynamically updated using time features in TOPAS.

matRad initiate the MC simulation and resume control at the end of TOPAS execution to extract the results written in binary format.

Examples of applications

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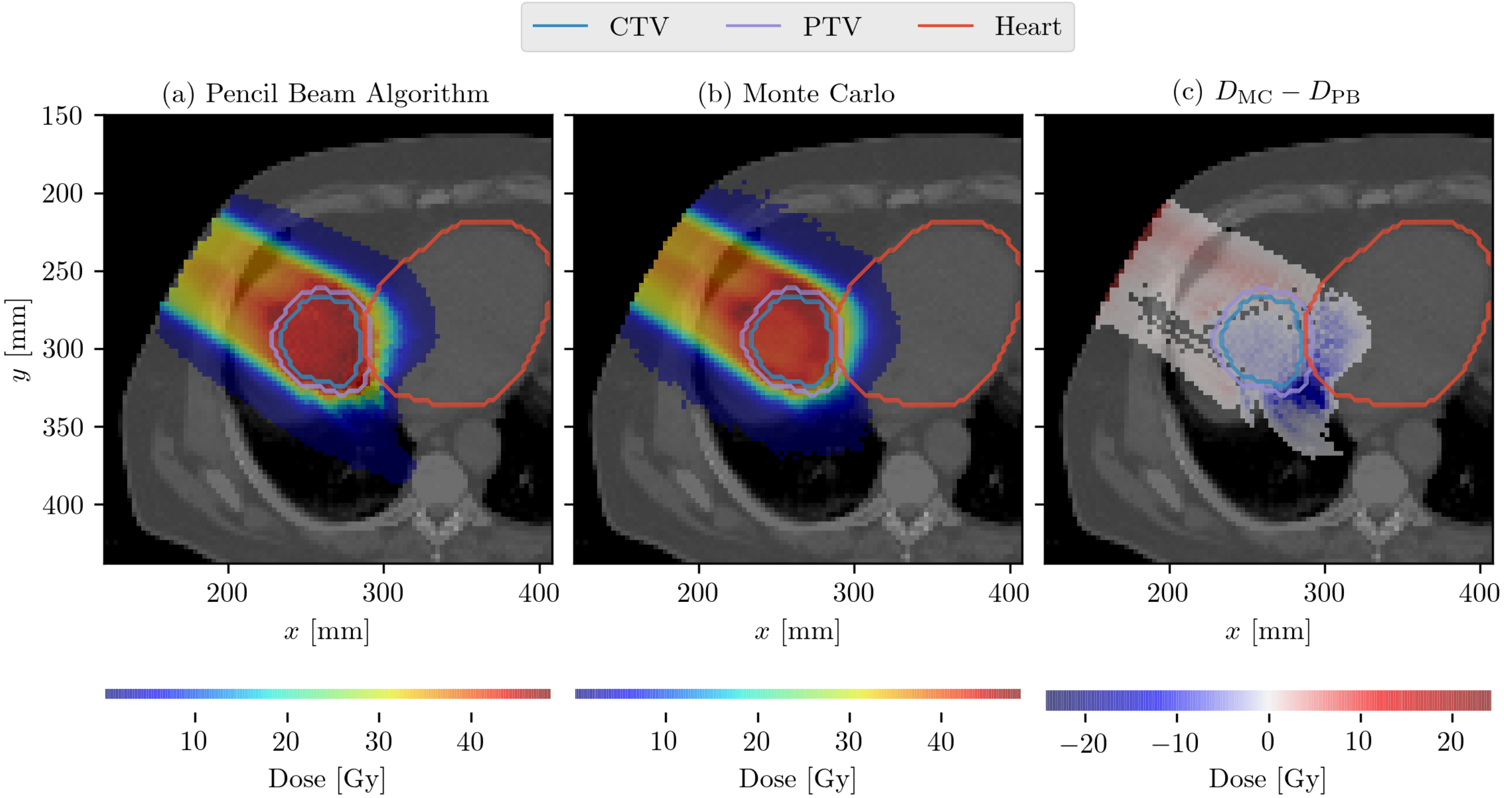
Pencil Beam vs Monte Carlo (MCsquare) Dose Calculation

Liver tumor (CORT dataset)



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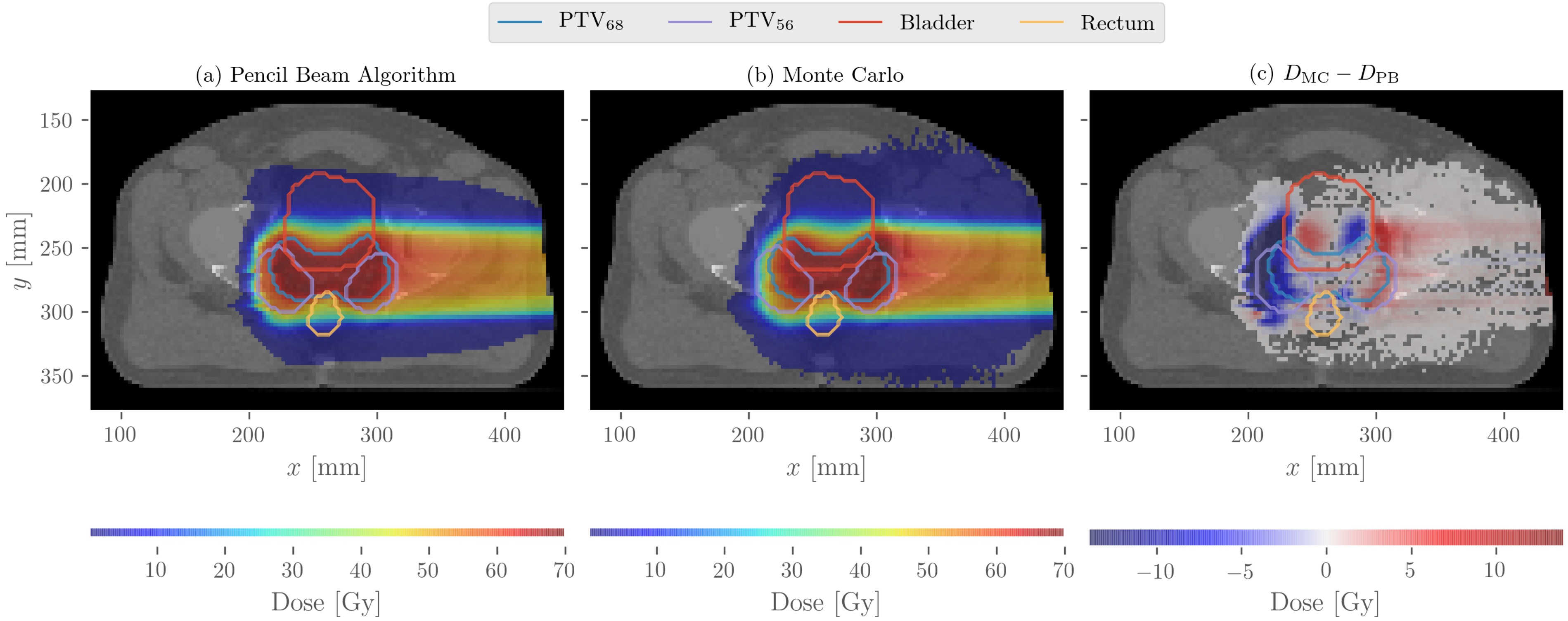
Pencil Beam vs Monte Carlo (MCsquare) Dose Calculation

Prostate cancer (CORT dataset)



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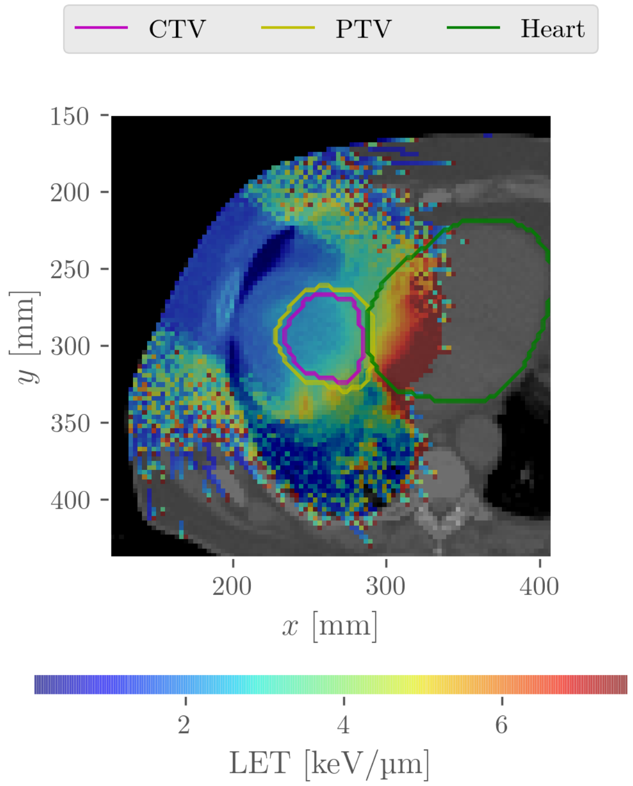
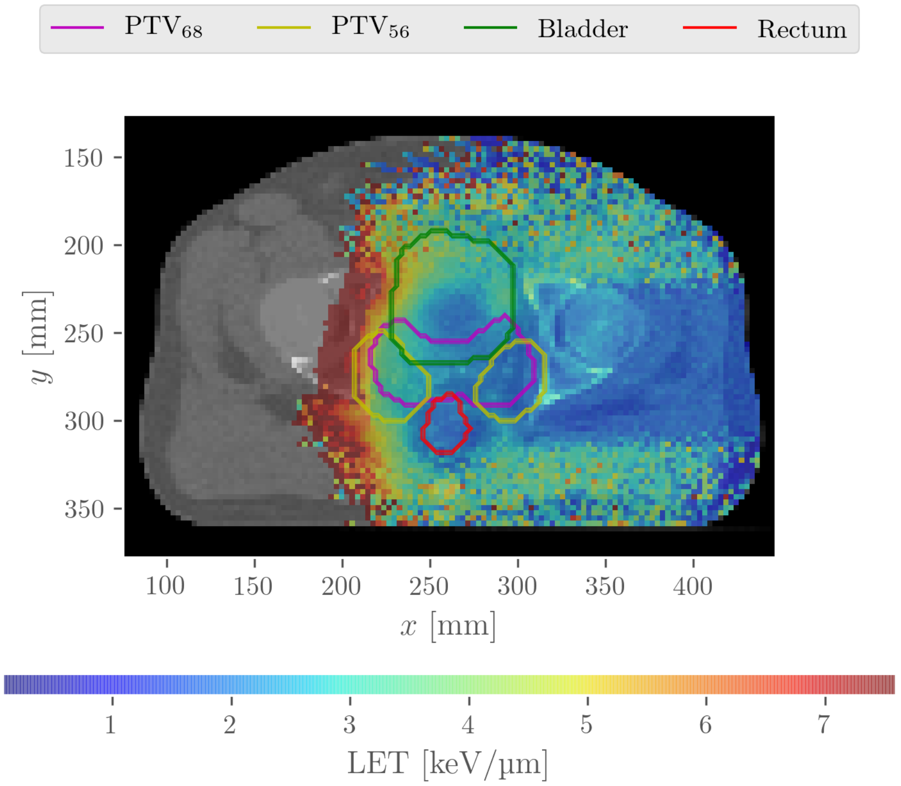
LET Calculation (MCsquare)

Liver tumor (CORT dataset)



Prostate cancer (CORT dataset)



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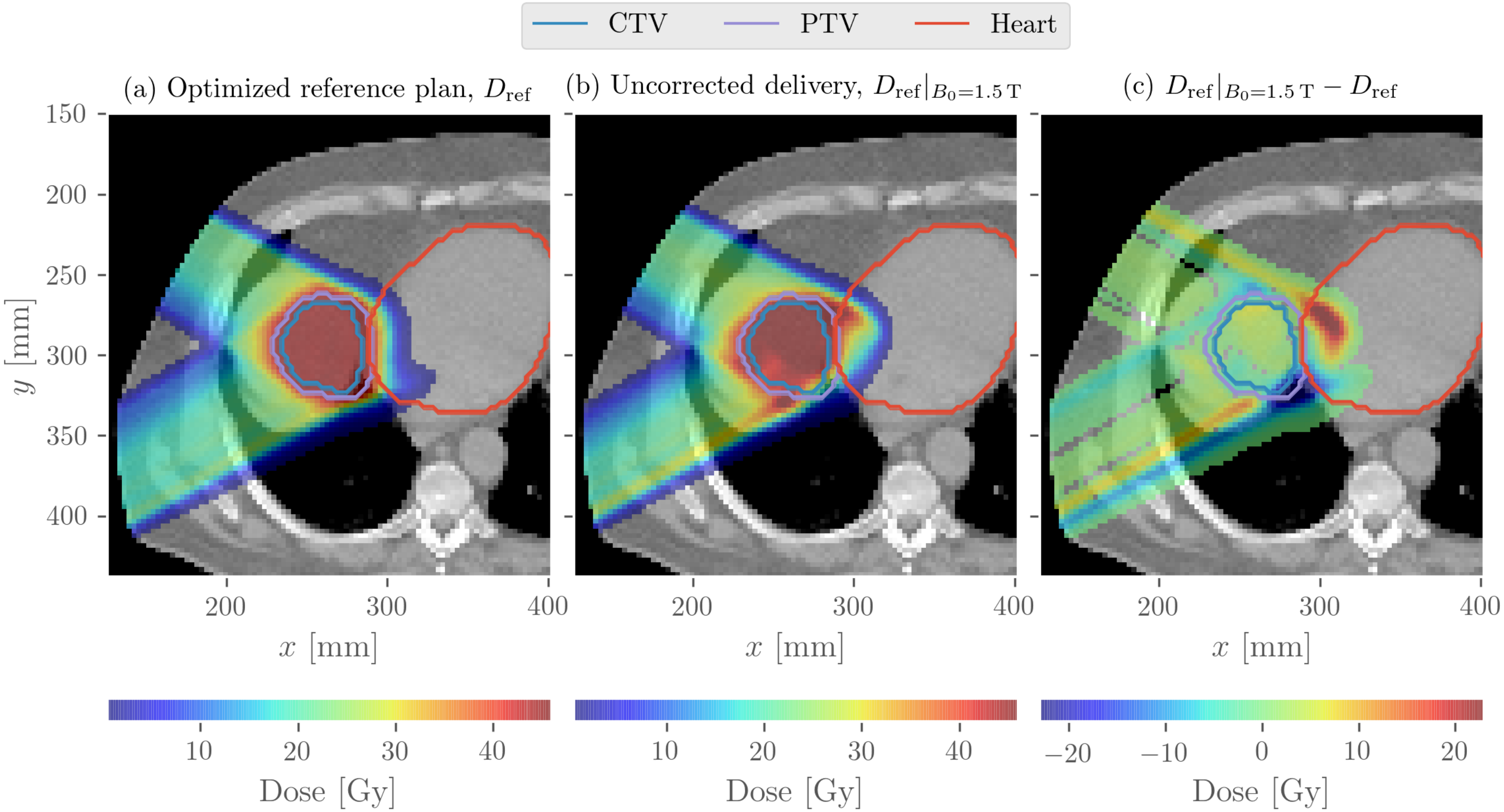
Monte Carlo (TOPAS) Dose Calculation in Magnetic Field

Liver tumor (CORT dataset)

Burigo and Oborn. *Phys Med Biol* 2019
doi:10.1088/1361-6560/ab436a



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Monte Carlo (TOPAS) Dose Calculation in Magnetic Field

Prostate cancer (CORT dataset)

Burigo and Oborn. *Phys Med Biol* 2019
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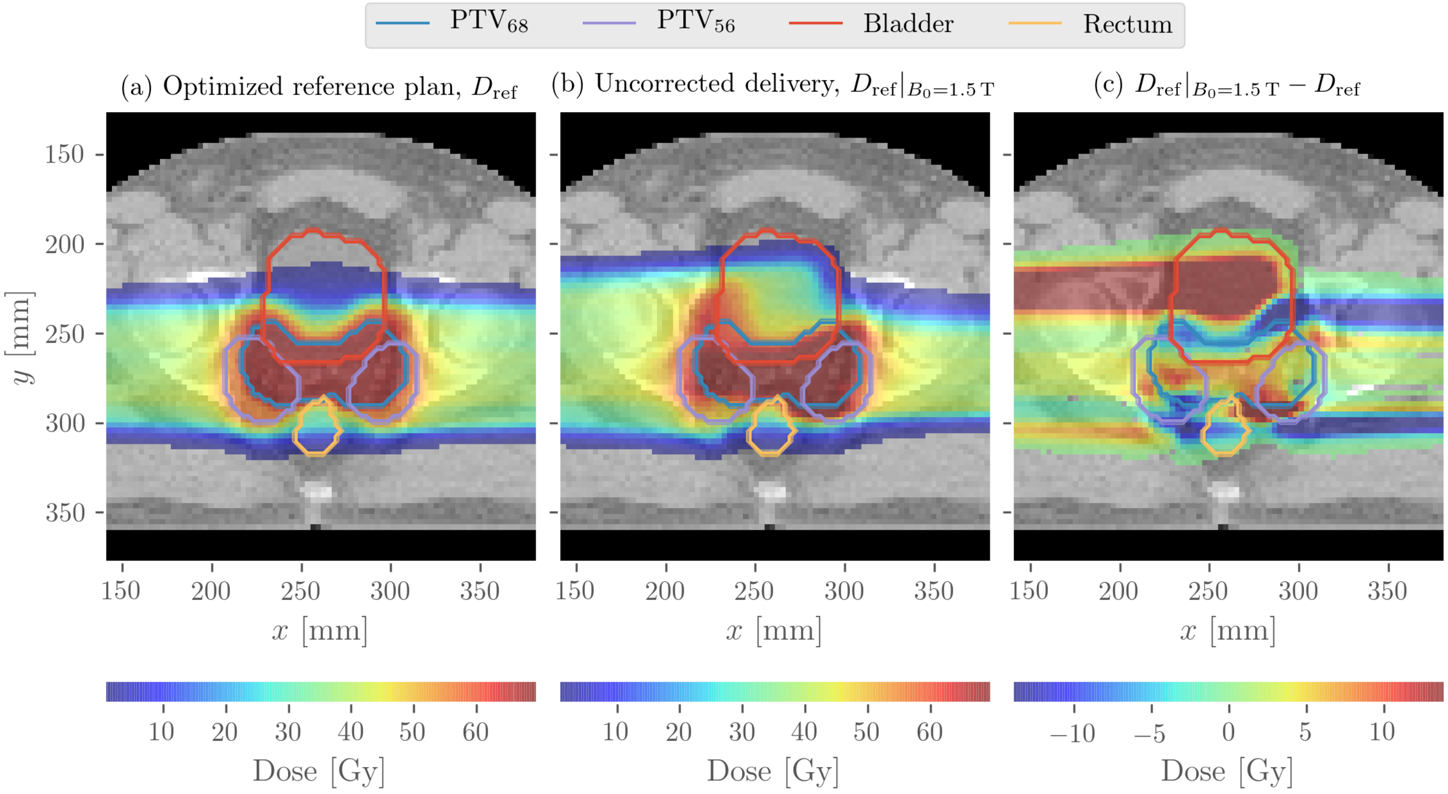

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Monte Carlo for more than dose calculation

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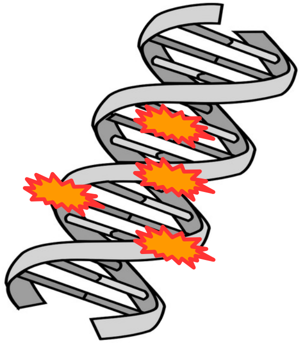
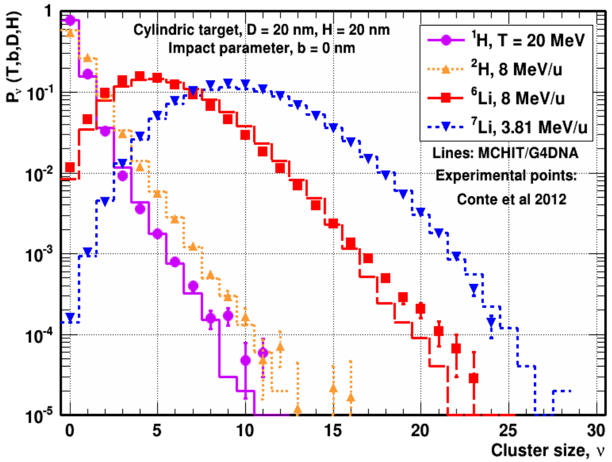
Nanodosimetry as alternative to LET

LET is not adequate to specify the radiation quality at the cell level as it gives no information on:
- fluctuations in energy loss
- lateral spread of the track



At the level of DNA structures, it is appropriate to specify the radiation quality by the **number of ionizations** taking place in the volume of interest.



Large ionization clusters (more than 3 ionizations in a distance of 10 base pairs) **correlates with complex DNA damages**.

Monte Carlo simulations can be used to model the **radiation-induced DNA damages** caused by impact ionizations and radical species.

Burigo *et al.* 2016 *Phys Med Biol* ***61***: 3698

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Computing ionization clustering in treatment planning

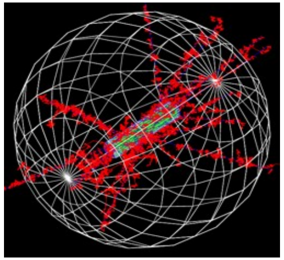
Ramos-Méndez et al *Phys Med Biol* 2018
doi:10.1088/1361-6560/aaeeee

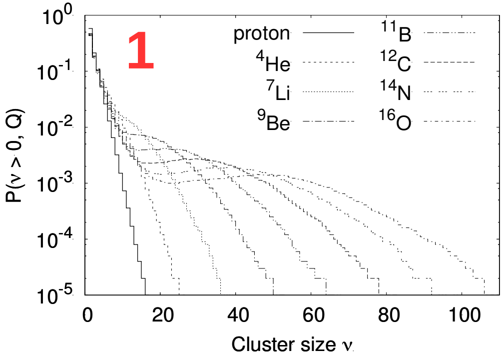
1. Nanodosimetry spectra for monoenergetic ions are calculated for random crossing of cylinders of 10 base pair length.

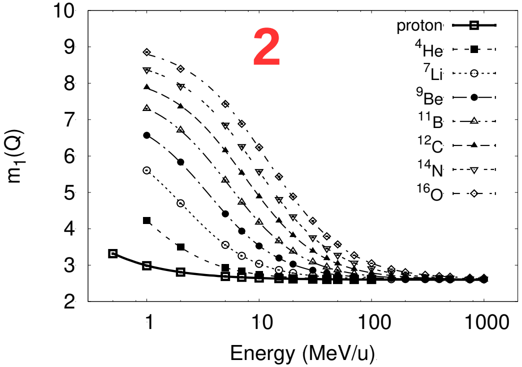
2. A look-up table of nanodosimetric quantities as a function of ion type and energy is generated.

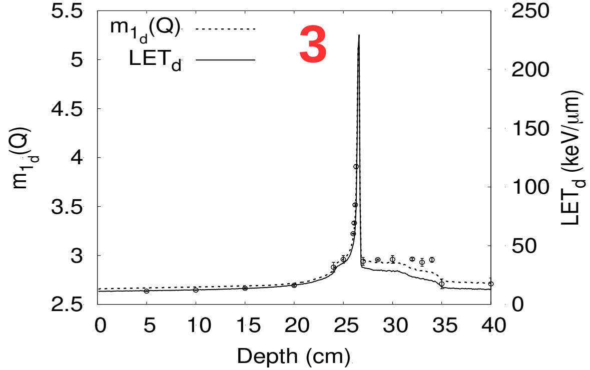
3. Nanodosimetric quantities are computed for each pencil beam

The matRad/TOPAS interface allows to compute the nanodosimetric distribution for the full IMPT plan.









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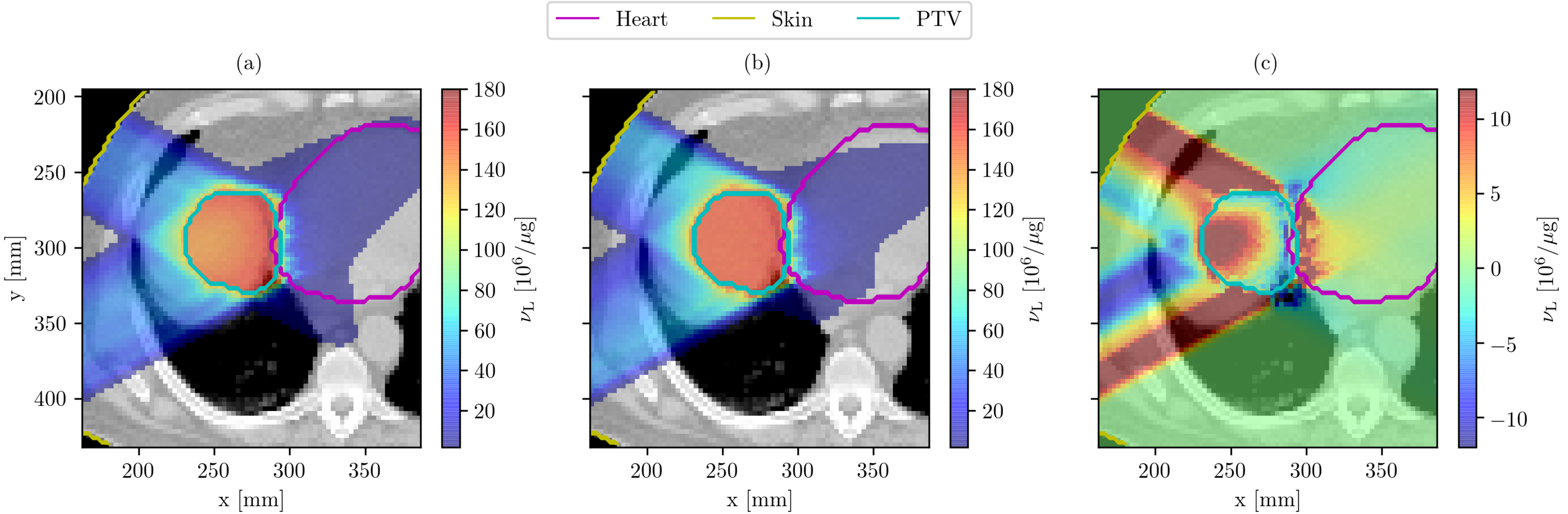
Simultaneous Optimization of Dose and Ionization Clustering

An **enhancement of the clinical potential** of IMPT can be expected from the **optimization of ionization clustering** in the target and OARs.



(a): plan with optimized uniform RBE-weighted dose for carbon-ion beams
(b): plan with optimized uniform RBE-weighted dose and large ionization clusters
(c): difference in specific number of large ionization clusters (b) – (a)

Burigo et al *Phys Med Biol* 2019
doi:10.1088/1361-6560/aaf400

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Thank you for your attention!

matRad

HP Wieser *et al* 2017. *Med Phys*
doi: 10.1002/mp.12251

www.matrad.org

Free Software

Free as in Freedom

GitHub

MATLAB

Interfaces

- DICOM
- *.nrrd, *.mha, *.vtk
- CERR
- VOXELPLAN

Dose calculation

- Photons
  - SVD decomposed pencil beam
  - OmpMC interface
- Particles
  - IMPT pencil beam
  - Monte Carlo interface (MCsquare & TOPAS)
  - Analytical probabilistic modeling

Analysis & visualization

- GUI CT & dose distribution browser
- Dose statistics
- DVHs

Dose optimization

- Fluence and experimental direct aperture optimization
- IPOPT https://projects.coin-or.org/Ipopt
- Matlab's proprietary fmincon
- Objectives: Quad. dose deviation, mean dose, EUD, DVH
- Constraints: Min, max, mean dose, EUD, DVH
- Xia, Engel, Siochi MLC sequencer
- Robust and stochastic optimization
- Variable RBE optimization for protons
- Coverage based optimization
- Analytical probabilistic modeling

Base data

- Patient data (CT & RTSS)
- Photon pencil beam base data
- Particle pencil beam base data
- Carbon-ion beam biological base data (LEM IV)
- Helium pencil beam base data
- Helium biological model

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