Deformable image registration of the treatment planning CT with proton radiographies in perspective of adaptive proton therapy

P. Palaniappan[1], S. Meyer[1,*], F. Kamp[2], C. Belka[2], M. Riboldi[1], K. Parodi[1] and C. Gianoli[1]

Ludwig-Maximilians-Universität München [1]
University Hospital, LMU Munich [2]
Now at: University of Pennsylvania[*]

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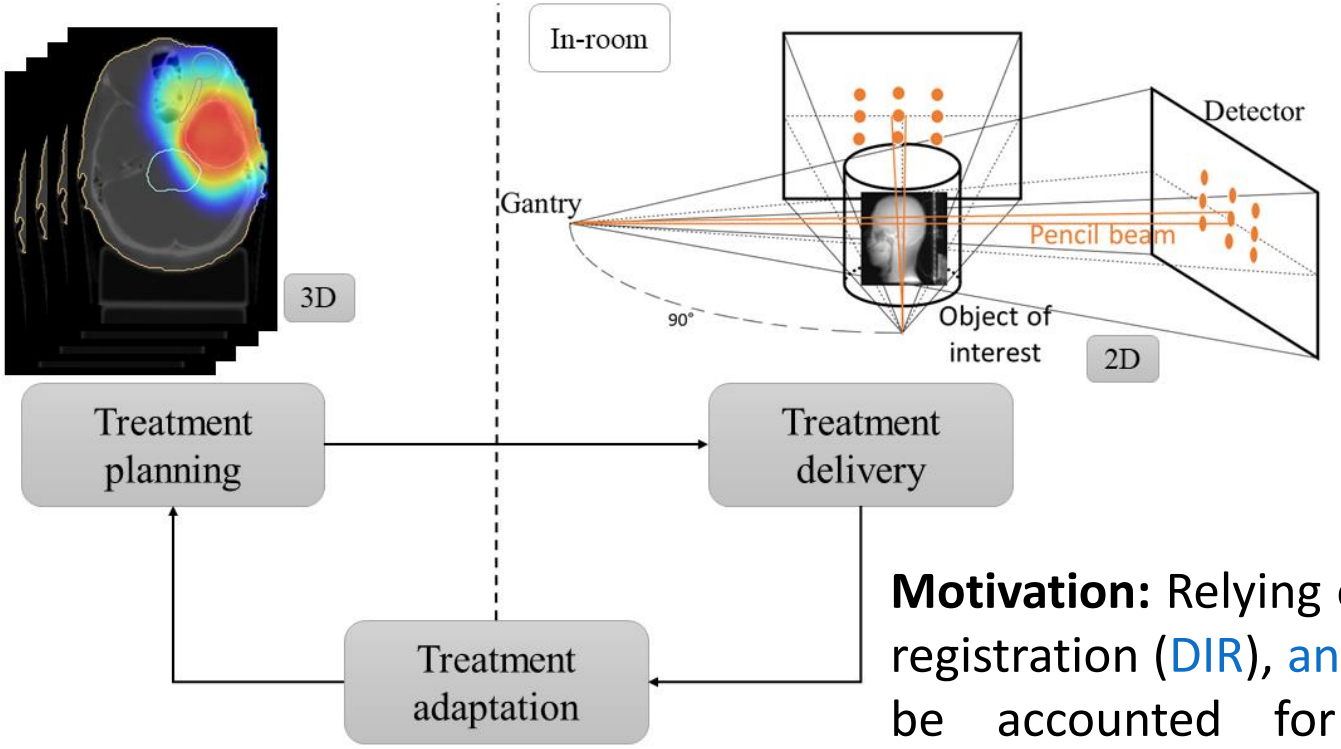
DIR with pRads in ART

Aim: Use in-room 2D proton radiographies (pRads) for Adaptive Radiation Therapy (ART)



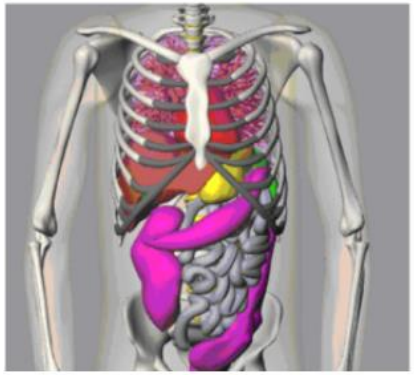
Motivation: Relying on deformable image registration (DIR), anatomical changes can be accounted for by adapting the treatment planning CT to the treatment delivery scenario (ART).

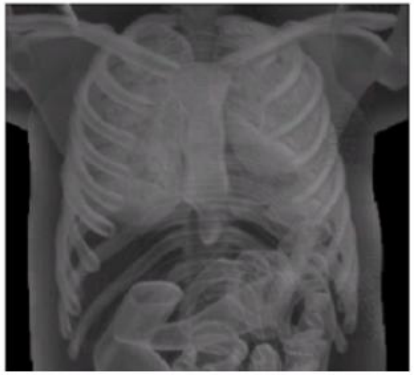
Framework

Development of 2D-3D DIR algorithm

Geometrical & Analytical simulation

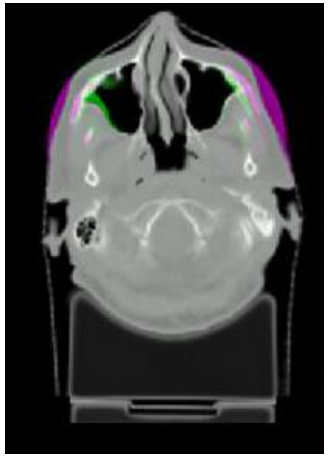
(Anthropomorphic phantom)





Monte Carlo simulation

(Clinical dataset)



Simulation (Phantom)

Geometrical simulation

Ideal pRads

Forward Projection of the ground truth proton CT calculating the WET as the integral RSP along a straight line.

Ideal pDRRs = forward-projection (applied to the calibrated treatment planning CT)

Analytical simulation

Individual Proton trajectories in pencil beam scanning (analytically simulated)

(Gianoli et al 2019)

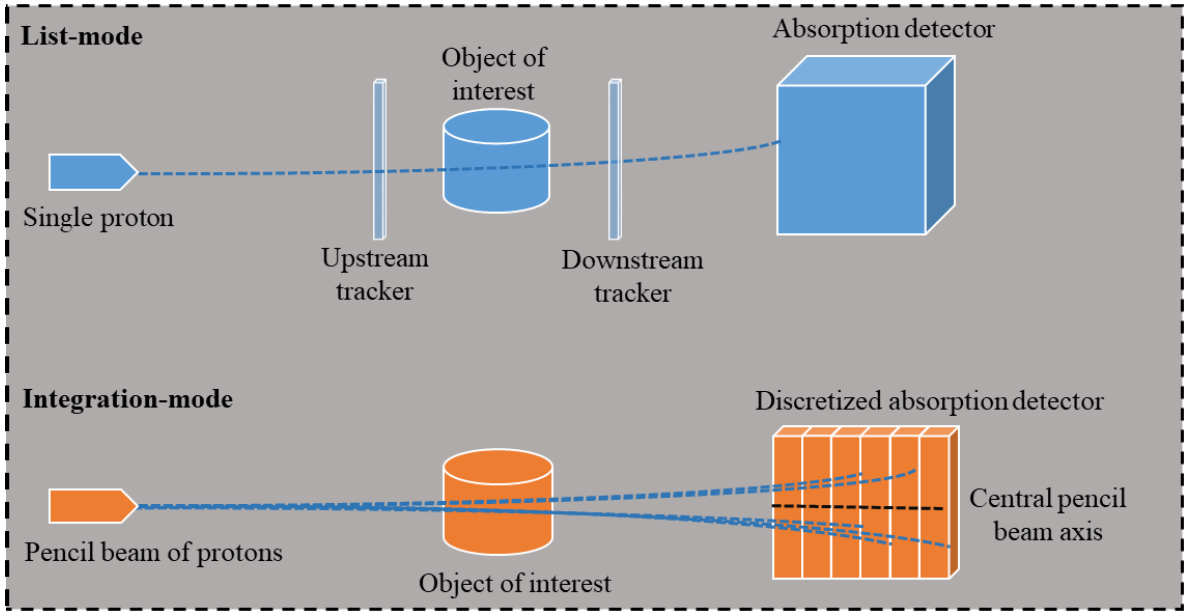
Trajectories (curved) are traced within the statistical distribution of a MCS model (originally given in uniform water and extended to non-uniform water equivalent materials) .

Trajectories deviates (due to MCS) from the central pencil beam axis in function of the RSP of the phantom

Each pencil beam with an energy of 280 MeV is composed by 25, 50, 75 and 100 protons per pencil beam.

(Gianoli et al 2019) Gianoli, C., Meyer, S., Magallanes, L., Paganelli, C., Baroni, G., & Parodi, K. (2019). Analytical simulator of proton radiography and tomography for different detector configurations. *Physica Medica*, *59*, 92-99.

Detectors



List-mode Rads:
Proton trajectory is estimated (pRads is composed by the WET for each proton of the pencil beam).

Integration-mode Rads:
Straight (most probable) central pencil beam axis is assumed (pRads, the exact solution of the mixed range signal, requiring linear decomposition in realistic integration-mode detectors)

Histogram (each pencil beam)

individual WET values weighted by the occurrences, mode *mean*	WET value with the maximum occurrence, mode *max*).

Simulation (Clinical data)

Monte Carlo simulation

A clinical CT image of a head and neck patient.

The ground truth pCT is adopted in Monte Carlo simulation of pRads from ideal list-mode and integration-mode detector configurations in pencil beam scanning.

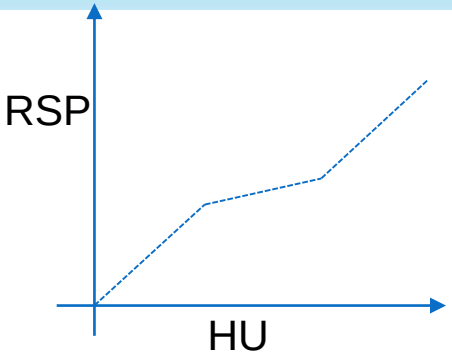
List-mode and integration-mode pRads and proton DRRs are obtained as for the analytical simulation.

The proton statistics is set equal to 400 protons per pencil beam (energy 199.94 MeV, pencil beam size 8.5 mm)

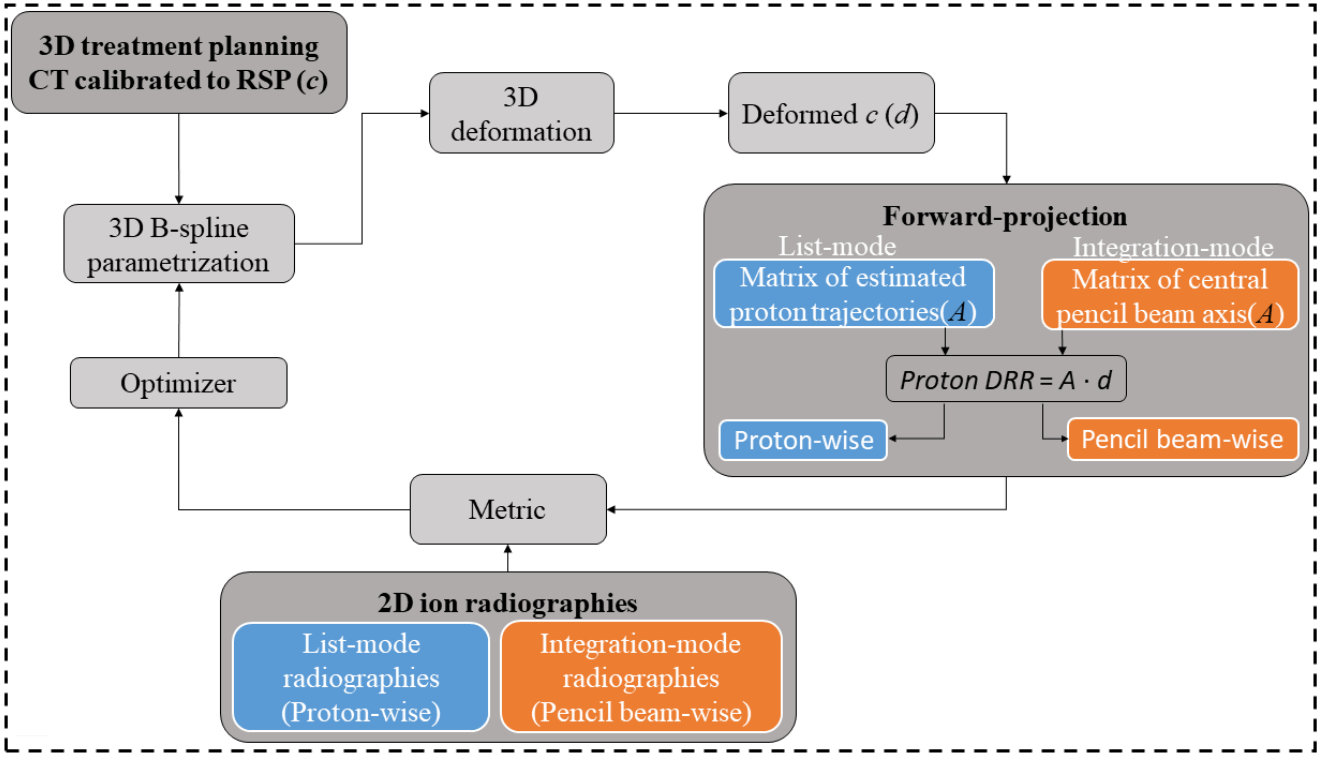
The proton interaction and transport are simulated in FLUKA (Meyer et al, 2019)

(Meyer et al 2019) Meyer, S., Kamp, F., Tessonnier, T., Mairani, A., Belka, C., Carlson, D. J., ... & Parodi, K. (2019). Dosimetric accuracy and radiobiological implications of ion computed tomography for proton therapy treatment planning. *Physics in Medicine & Biology*, *64*(12), 125008.

2D-3D DIR framework



CT calibration is typically empirical → discrete calibration curve that maps HU to RSP (relative stopping power)



Metric (RMSE, NMI), Optimizer (BFGS)

Anatomical changes

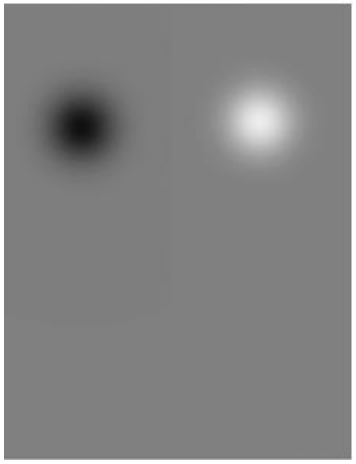
Anthropomorphic phantom: The breathing is modeled by Non Uniform Rational Basis-Splines relying on a superior-inferior diaphragm motion and an anterior-posterior chest wall expansion curves.

The image size of the phantom is 128×128×100 voxels and the voxel size is 3×3×3 mm^3.

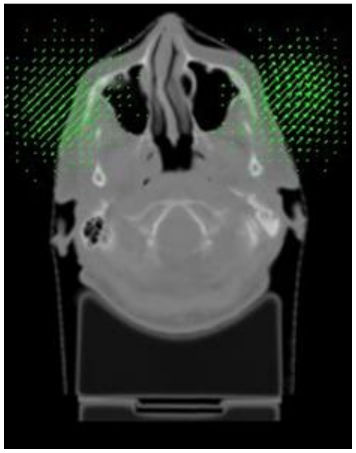
Anatomical changes

Clinical dataset: Gaussians of opposite signs for each component are laterally placed on different position to simulate weight loss. The Gaussian amplitude and standard deviation are ±8 mm and 16 mm, respectively.

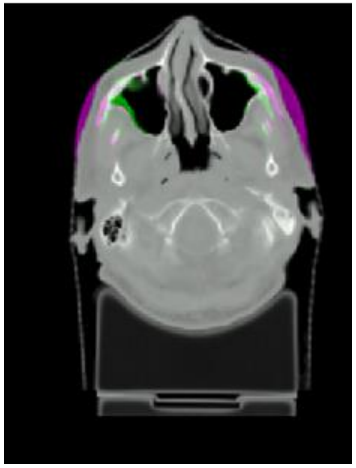
Component of the deformation field



Deformation field



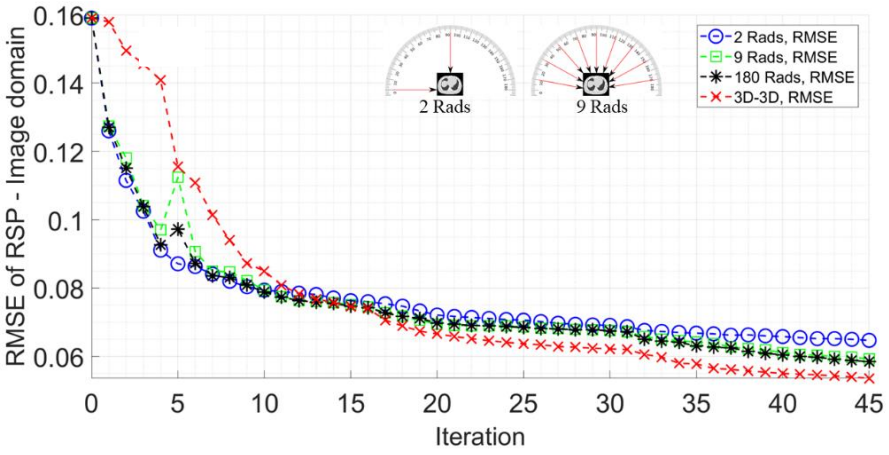
Anatomical changes (overlay)

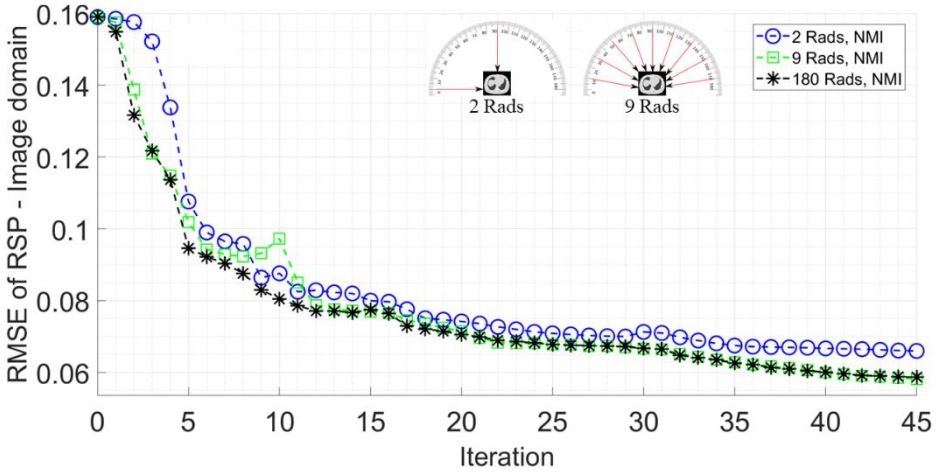


The CT image 314×314×10 voxels.
Pixel size is 0.1074 x 0.1074 cm^2 and the slice thickness is 0.3 cm.

Results - Phantom

Geometrical simulation

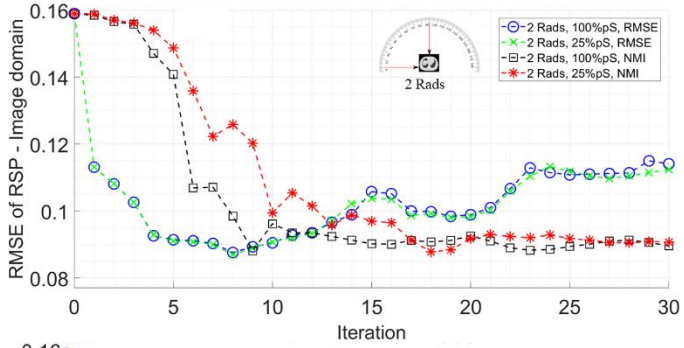


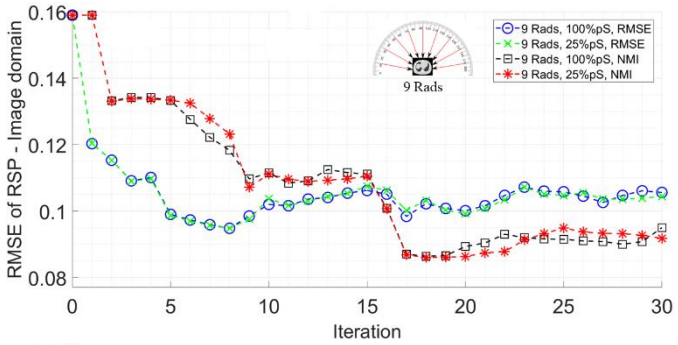


Objective function (Metric) - **RMSE** **NMI**

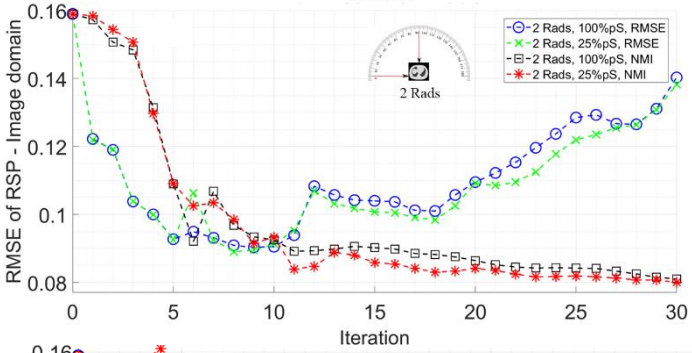
Results - Phantom

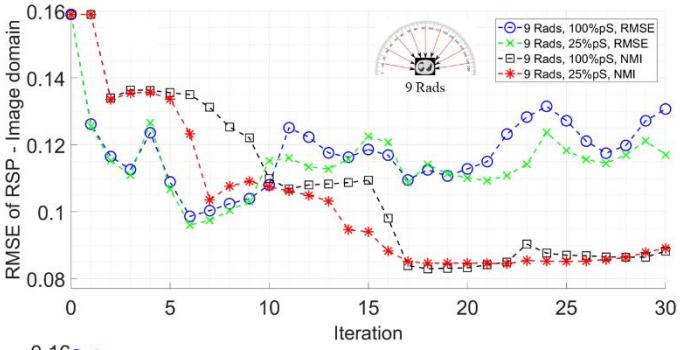
Analytical simulation



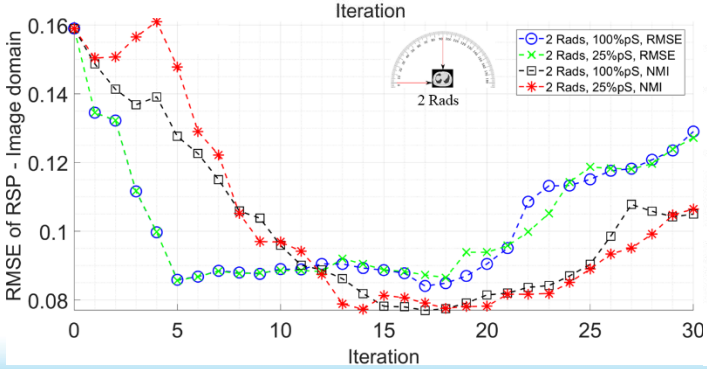


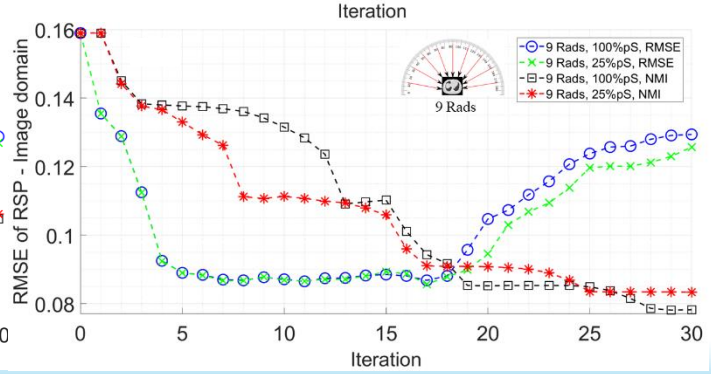
Integration-mode ***mean***





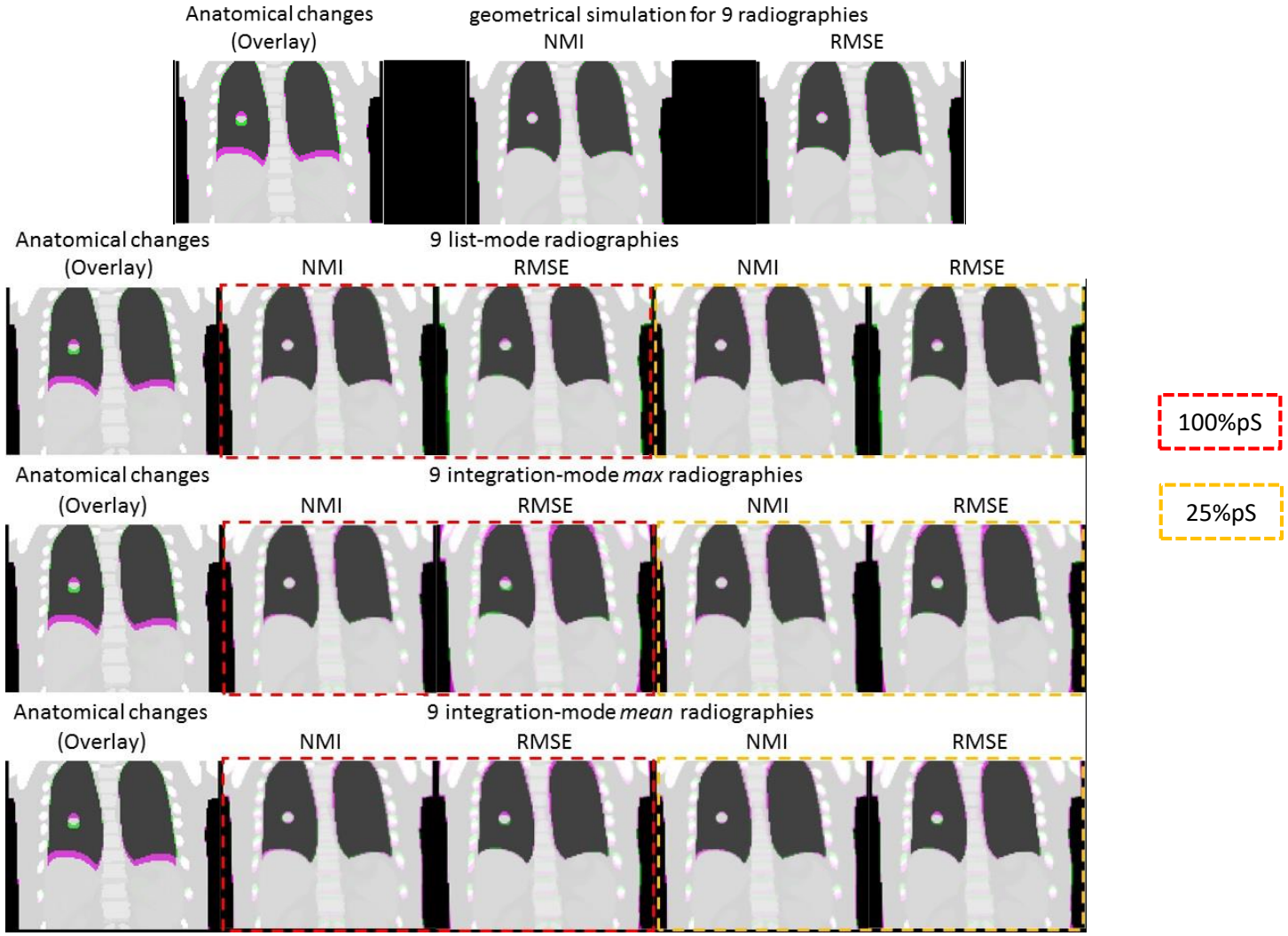
Integration-mode ***max***





List-mode

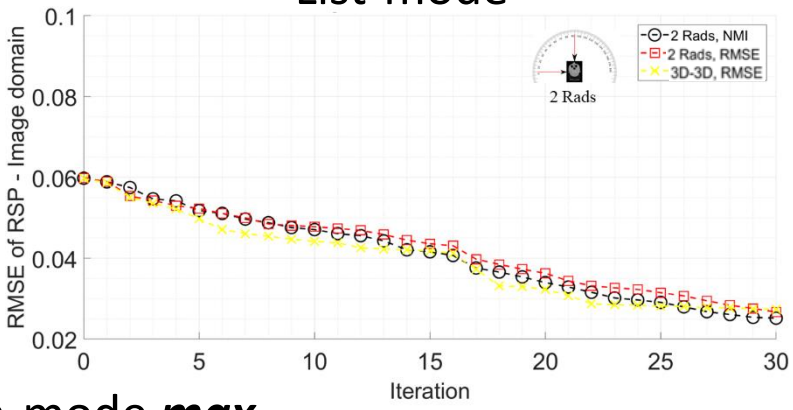
Results - Phantom



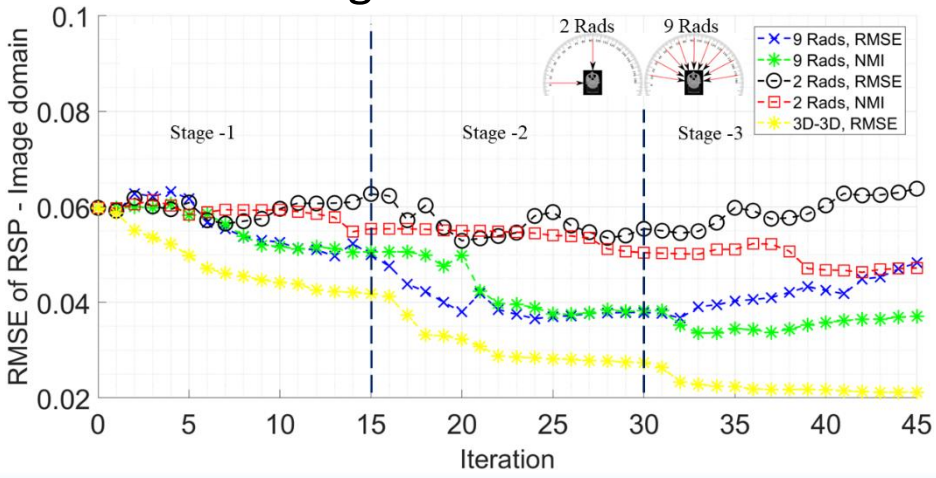
Results - Clinical data

Monte Carlo simulation of clinical data

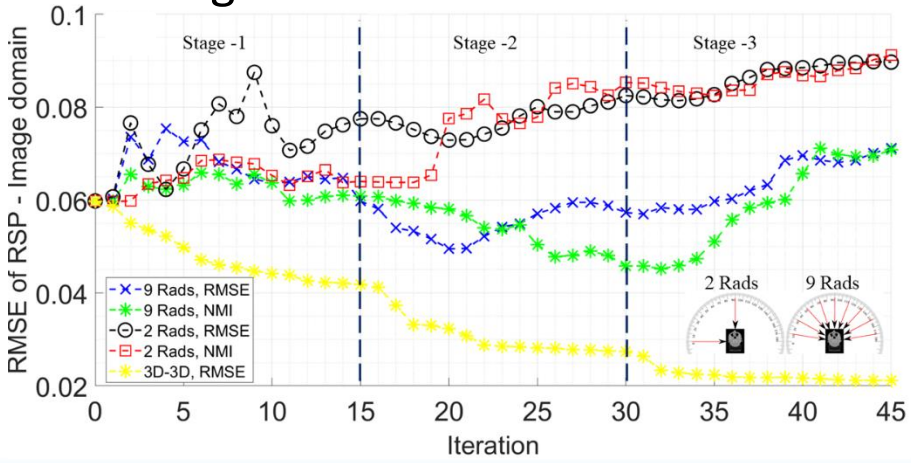
List-mode



Integration-mode ***max***



Integration-mode ***mean***

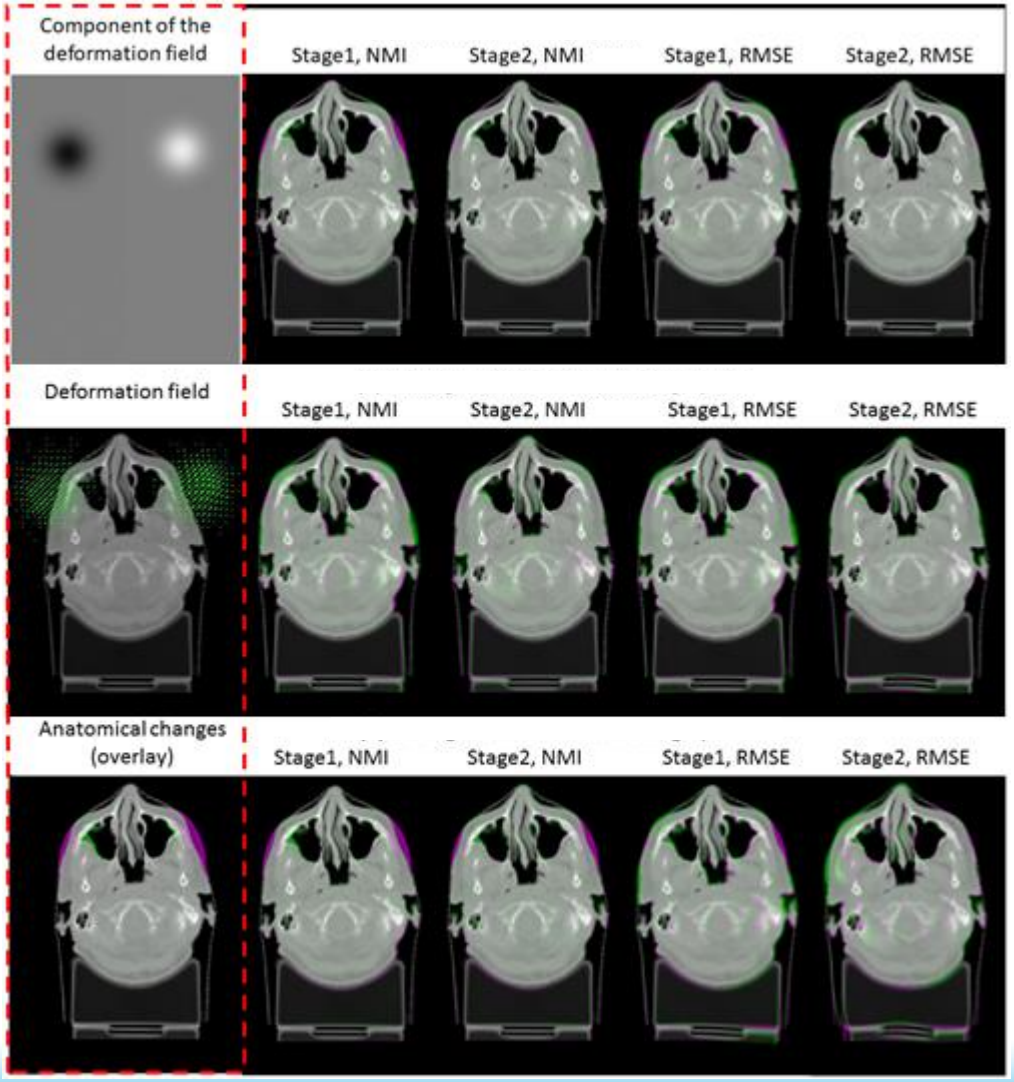


Results - Patient

List-mode, 2 Rads

Integration-mode *max*, 9 Rads

Integration-mode *max*, 2 Rads



Stage1 : 64 grid spacing
Stage2 : 32 grid spacing

Results – Evaluation

Geometrical simulation

Relative change in RMSE of RSP with respect to 180 proton radiographies

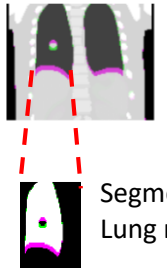
	9 Rads	8 Rads	7 Rads	6 Rads	5 Rads	4 Rads	3 Rads	2 Rads
RMSE	1.37%	1.53%	2.39%	3.07%	4.79%	4.79%	7.35%	10.6%
NMI	-0.85%	-0.68%	1.19%	1.73%	2.21%	3.24%	7.84%	12.44%

180 Rads (RMSE of RSP equal to 0.0585).

3D-3D DIR (RMSE of RSP equal to 0.0536)

Dice similarity coefficient on segmented organs(closer the value to 1 better the accuracy)

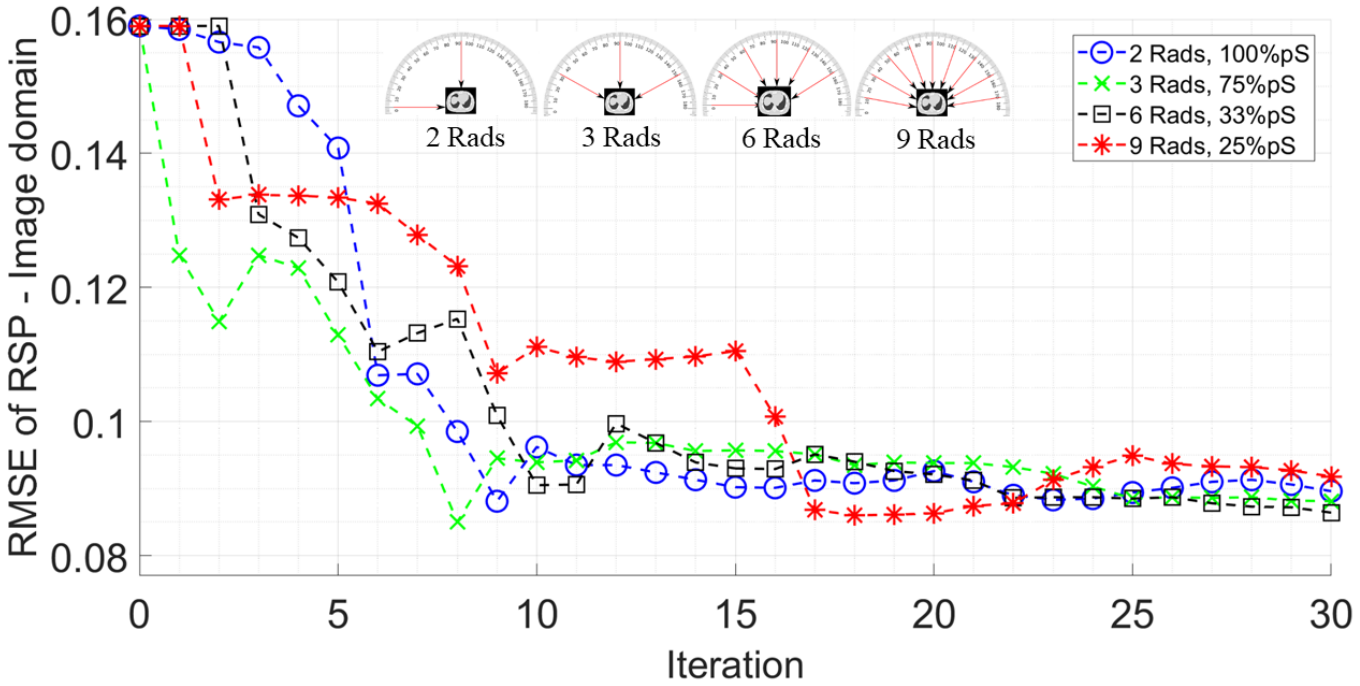
	Prior DIR	After 2D-3D DIR						After 3D-3D DIR
		2 Rads NMI	*2 Rads RMSE*	*9 Rads NMI*	*9 Rads RMSE*	*180 Rads NMI*	*180 Rads RMSE*	
Heart	0.67	0.78	0.78	0.79	0.79	0.79	0.78	0.78
Liver	0.87	0.92	0.92	0.93	0.93	0.93	0.93	0.92
Lesion	0.43	0.79	0.81	0.68	0.72	0.69	0.68	0.84
Lung	0.91	0.97	0.97	0.96	0.96	0.96	0.97	0.97



Segmented Lung region

Results – Proton Statistics

Analytical simulation



Different pS (NMI as objective function) in analytical simulation of integration-mode *mean*

Conclusions

- Firstly investigated a 2D-3D DIR using a limited number of pRads to compensate the anatomical changes in the treatment delivery scenario with respect to the treatment planning CT.

- List-mode and integration-mode pRads with different proton statistics are simulated to compare the performance of different detector configurations.

- Minimum number of radiographies depends on the amount and the complexity of the anatomical changes and the adopted detector configurations but less on proton statistics, thus allowing the usage of low dose pRad.

Outlook

- In 2D-3D DIR - Stopping criteria have to be introduced relying on a critical evaluation of the adopted metrics, especially when disagreeing deteriorations of different metrics are observed.

- Realistic anatomical changes combined with rigid patient position inaccuracies.

- Information about RSP will be derived, thus enabling the combination of the 2D-3D DIR with the optimization of the empirical calibration of the treatment planning CT directly based on the adopted pRads (Gianoli et al, 2020).

- A framework, either sequential or joint implementation of the two methodologies, thus making the most of the native in-room radiographic imaging in proton therapy.

(Gianoli et al, 2020) Gianoli, C., Göppel, M., Meyer, S., Palaniappan, P., Rädler, M., Kamp, F., Belka, C., Riboldi, M. and Parodi, K., 2020. Patient-specific CT calibration based on ion radiography for different detector configurations in 1H, 4He and 12C ion pencil beam scanning. Physics in Medicine & Biology.

Thank you for your attention!

P. Palaniappan[1], S. Meyer[1,*], F. Kamp[2], C. Belka[2], M. Riboldi[1], K. Parodi[1] and C. Gianoli[1]

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