4D Monte Carlo simulation to assess the impact of respiratory motion during radiation therapy

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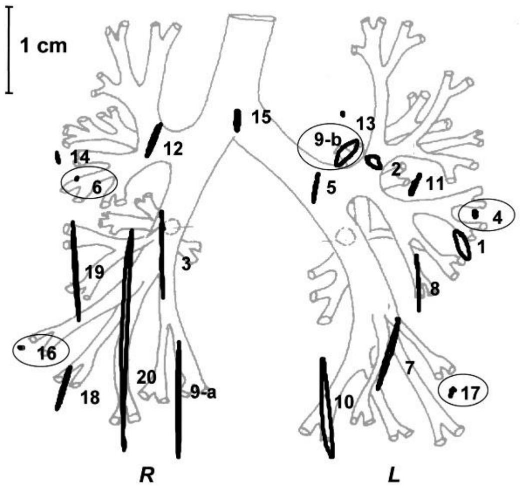
Outline

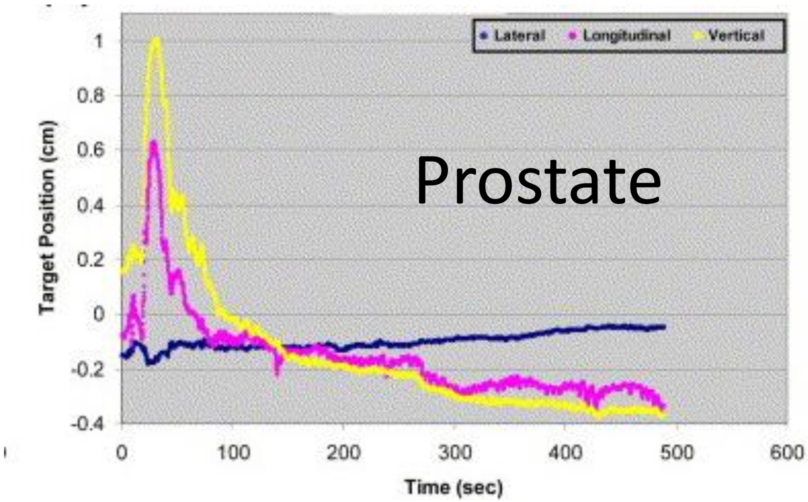
- Motion in radiation therapy
- Modeling dosimetric impact of motion
- 4D Monte Carlo simulation
- Experimental validation
- Needs and future work

Motion in radiation therapy

- Respiratory motion (thorax, abdomen)
- Digestion, bladder filling (pelvis)
- Motion characteristics are patient-specific



Seppenwoolde et al., International Journal of Radiation Oncology*Biology*Physics, 53(4), 2002.

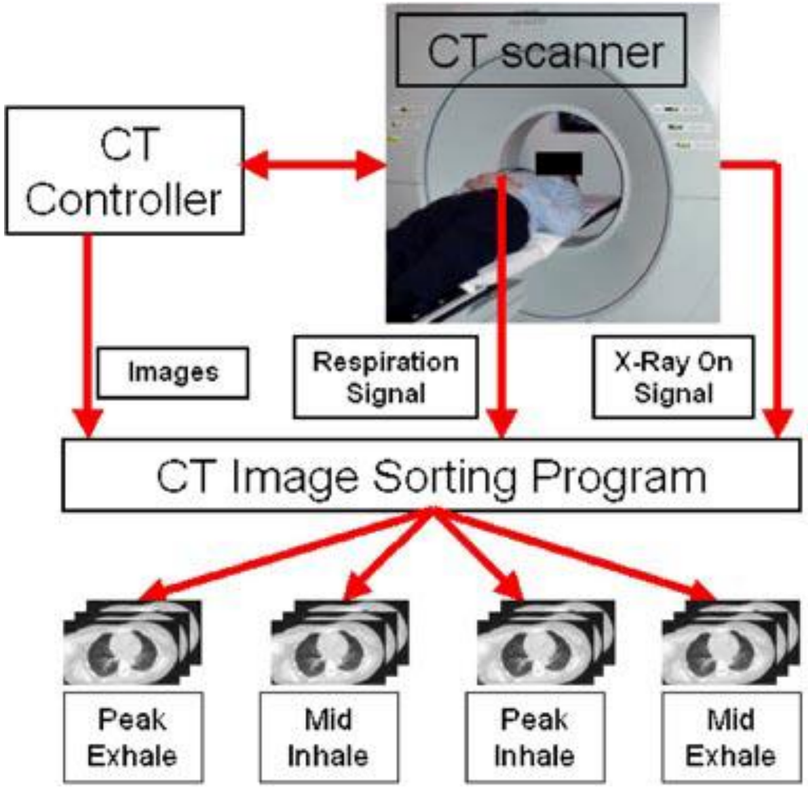


Prostate

Willoughby et al., International Journal of Radiation Oncology*Biology*Physics, 65(2), 2006.

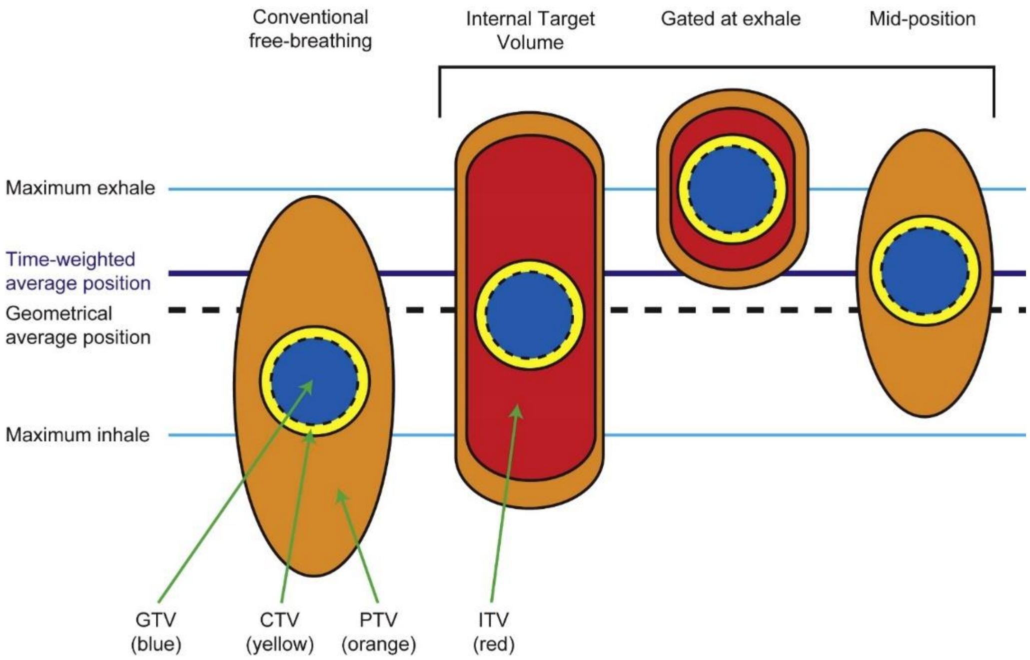
Motion management techniques

4D imaging for individual patient motion assessment



Vedam et al Phys. Med. Biol. 48, 2003.

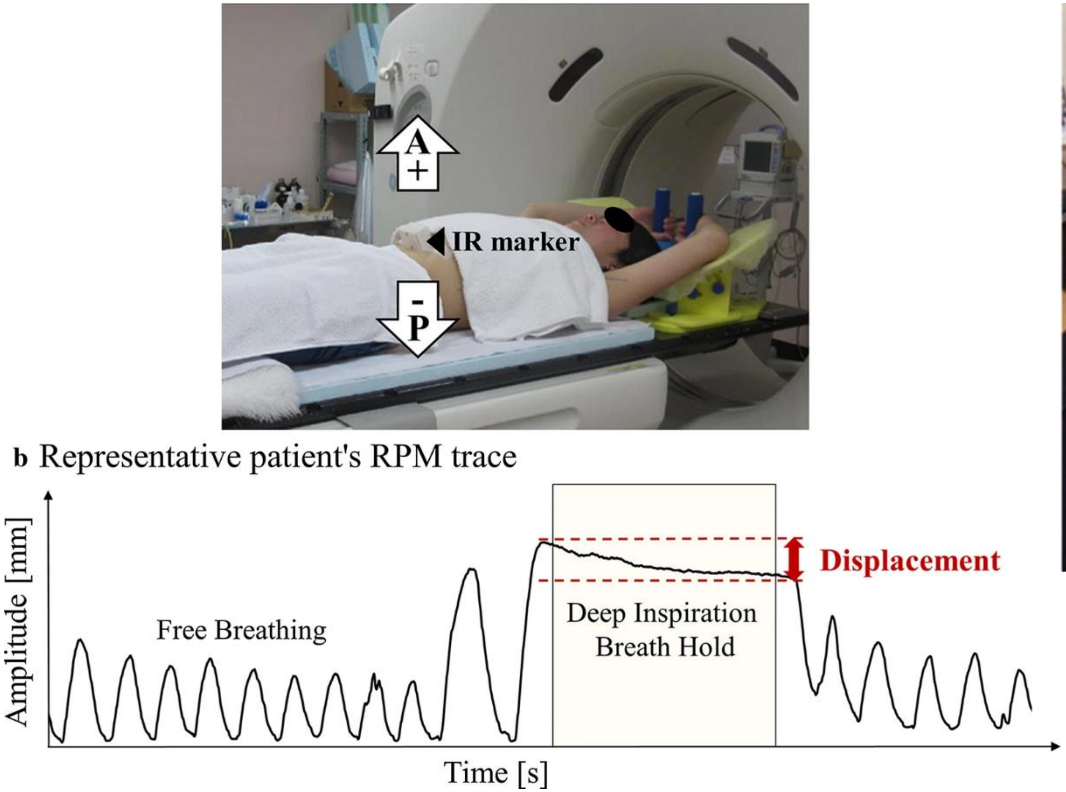
Treatment planning margins (motion encompassing or probabilistic)



Wolthaus et al., International Journal of Radiation Oncology*Biology*Physics, 70(4), 2008

Motion management techniques

Breath hold



Ono et al. Radiat Oncol 16(49), 2021.

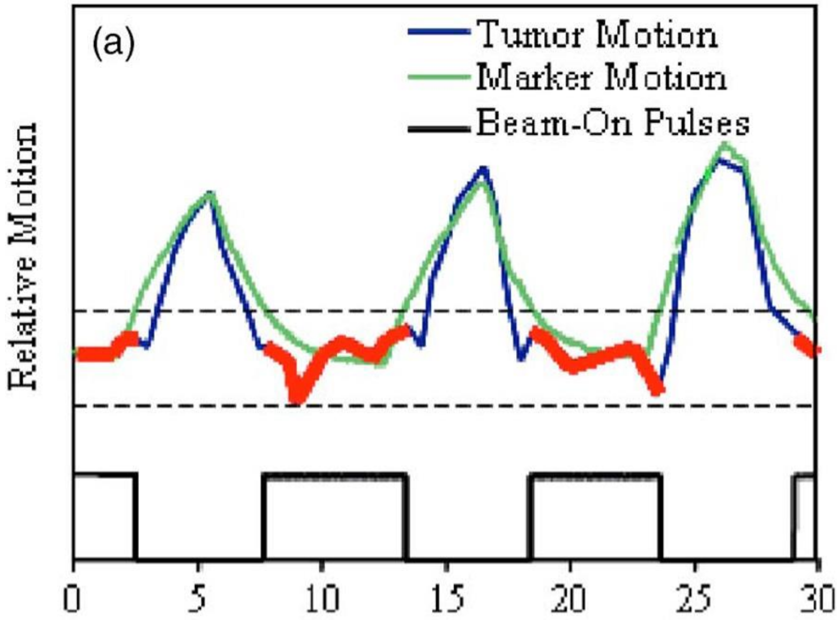
Abdominal compression

Mampuya et al., Med. Phys. 40(9), 2013.

Motion management techniques

Gating

Tumour tracking



Keall et al., Med. Phys. 33, 2006.

https://cyberknife.com/cyberknife-technology/

Need for 4D dose calculation

- **Prospective** – comparing motion management methods (resource allocation)
- **Retrospective** – quality assurance of patient dose delivery
- **Real-time** – real-time motion adapted radiation therapy

Modeling dosimetric impact of motion

- **Blurring** of the dose distribution

Dose/fluence convolution

- **Localized dose deformations** at interfaces between tissues of different densities (breakdown of spatial invariance assumption -> important for charged particles)

- **Interplay effects** for dynamic beam delivery

Modeling dosimetric impact of motion

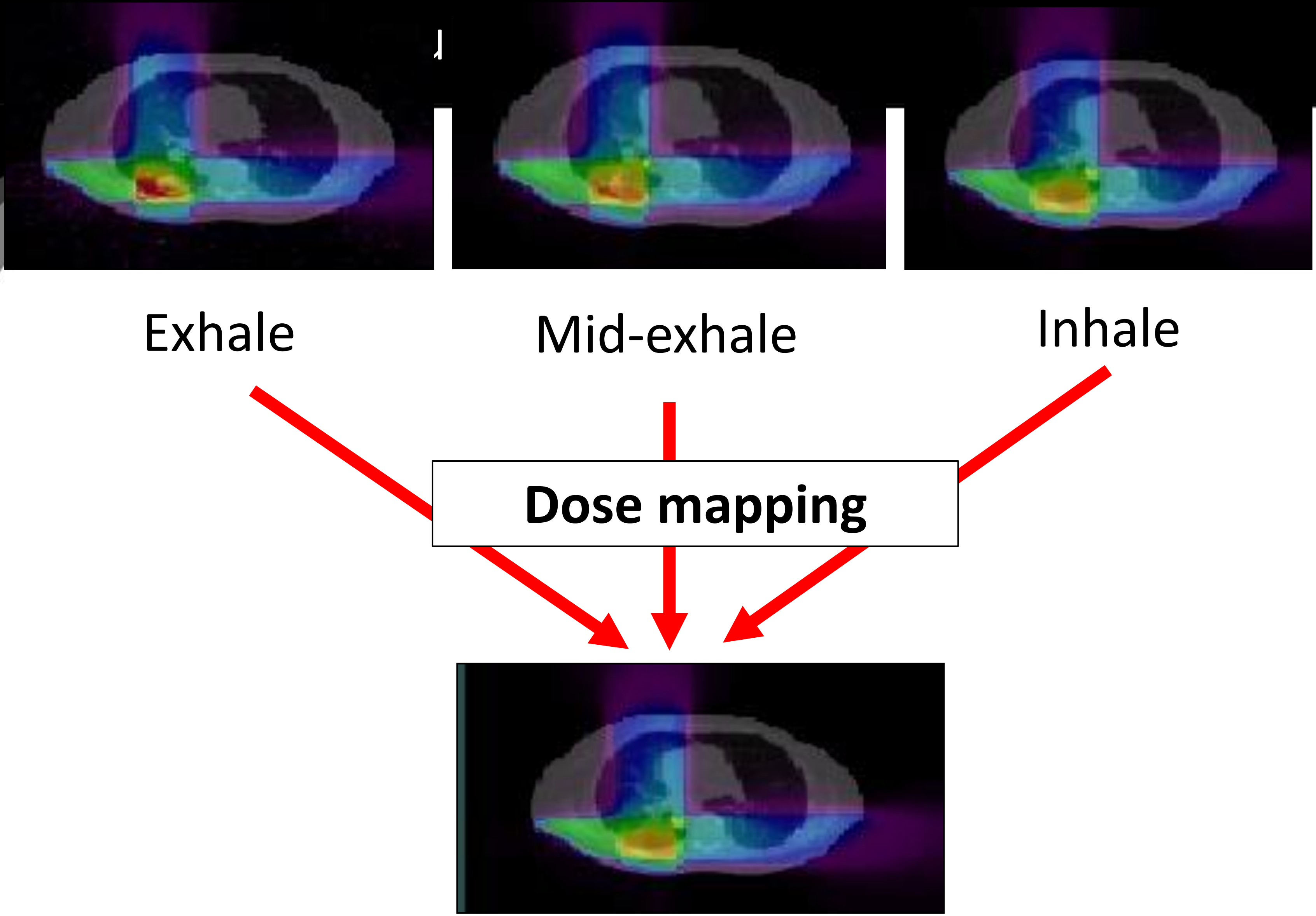
- **Blurring** of the dose distribution

~~Do[illegible]nce~~
~~co[illegible]on~~

- **Localized dose deformations** at interfaces between tissues of different densities

Calculate the dose delivered on multiple anatomical instances

- **Interplay effects** for dynamic beam delivery



Exhale

Mid-exhale

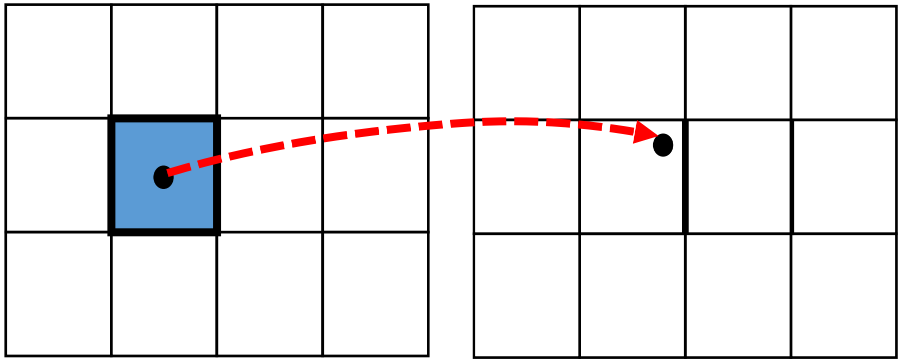
Inhale

Dose mapping

Cumulative dose on Reference Geometry

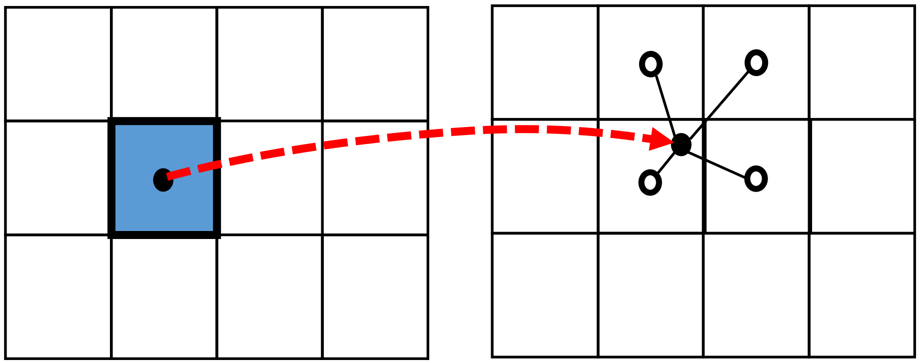
Dose mapping

- Tracking dose to tissue elements whose voxel coordinates are changing
- Requires a geometrical mapping between reference and target geometries



$$D_R(i) = D_T(i)$$

COM mapping



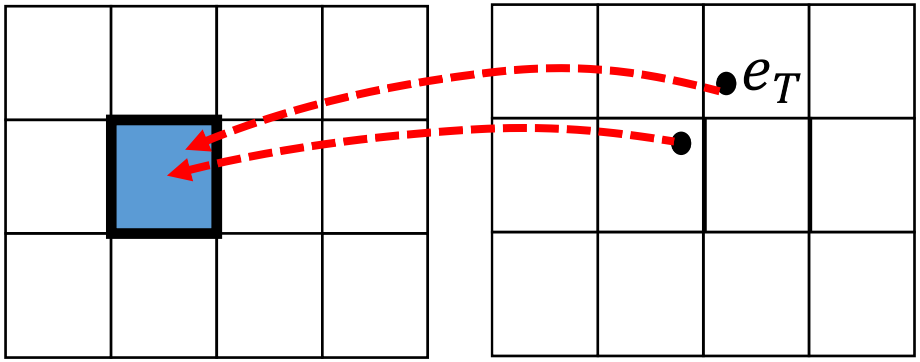
$$D_R(i) = \sum w_j D_t(j)$$

Trilinear interpolation

Energy conservation in dose mapping

- Dose mapping does not conserve the deposited energy
- Two energy-conserving methods:

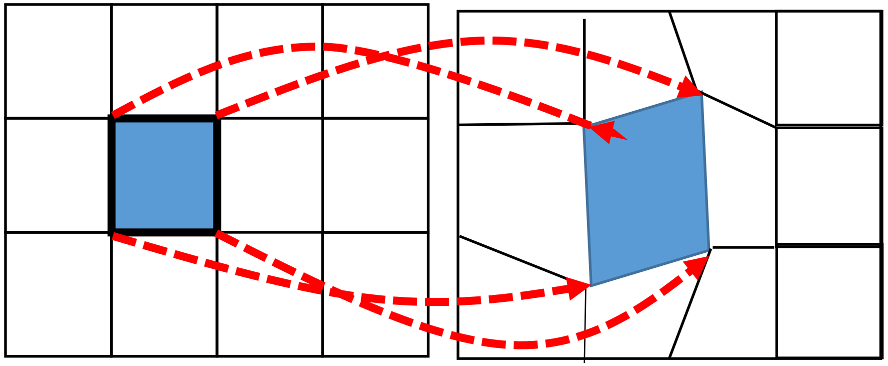
Energy mapping



$$D_R(i) = \frac{\sum e_T'(i)}{m_R(i)}$$

Siebers and Zhong Med. Phys., 2008

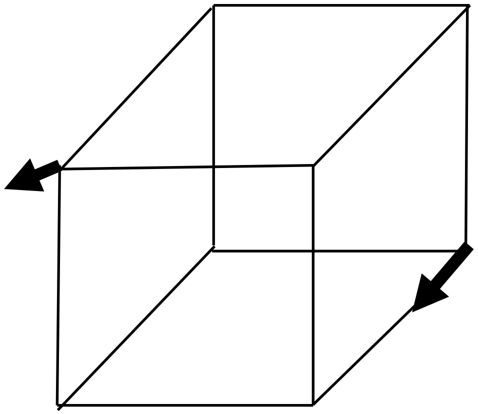
Deforming voxels



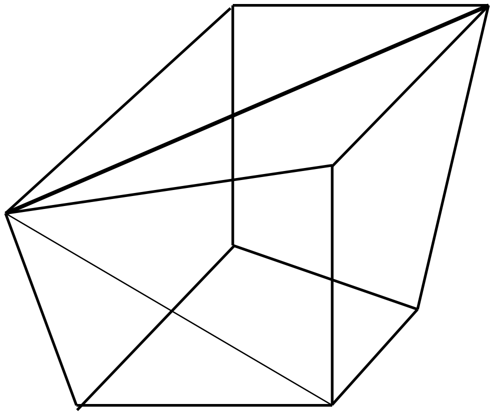
Heath and Seuntjens, Med. Phys. 33(2), 2006.

Deforming voxels implementation

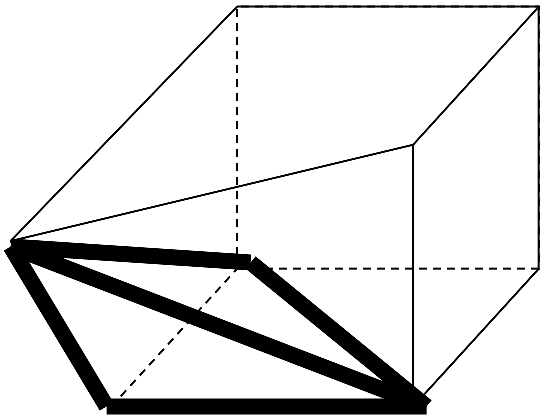
- Apply deformations to voxel nodes
- 2 geometries investigated: dodecahedrons (defDOSXYZnrc) and tetrahedrons (defVMC++)



Reference voxel + deformation vectors



Dodecahedron



Tetrahedral element

Computational efficiency comparison

Test case	**Calculation**	**Efficiency (1/s)**	**Ratio**
Rectangular Phantom	VMC++ XYZ	9985	-
	VMC++ defVox	1986	0.20
	VMC++ defTetra	5115	0.51
Lung Patient (Exhale-Inhale)	VMC++ XYZ	667	-
	VMC++ defVox	112	0.17
	VMC++ defTetra	190	0.28

Computational efficiency

$$\varepsilon = \frac{1}{\sigma^2 T}$$

Modeling dosimetric impact of motion

- **Blurring** of the dose distribution

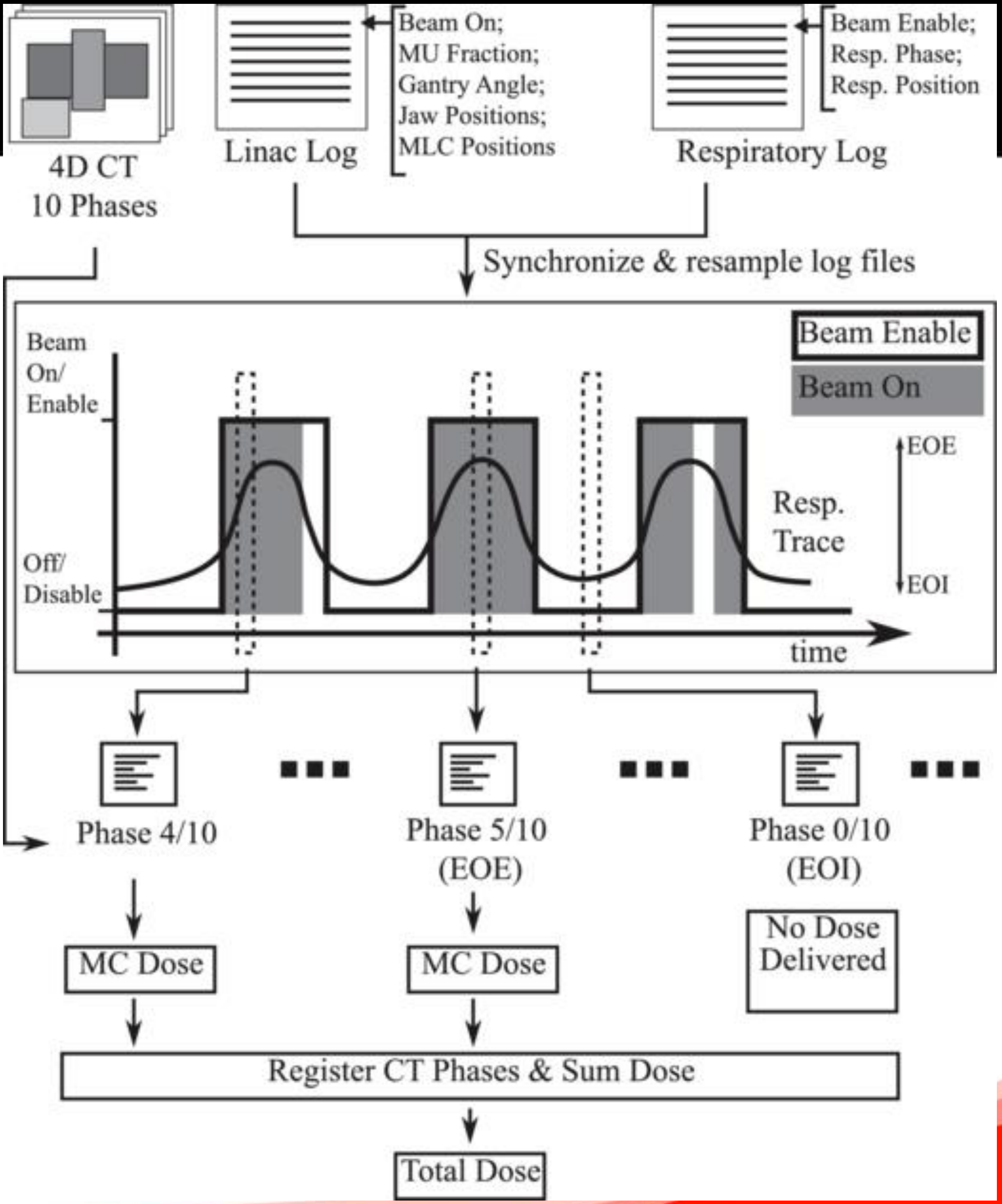
~~Convo with a~~
~~mot rnel~~

- **Localized dose deformations** at interfaces between tissues of different densities (breakdown of spatial invariance assumption)

Calculate the dose delivered on multiple anatomical instances

- **Interplay effects** for dynamic beam delivery

Correlate sub-beam delivery to current anatomical state



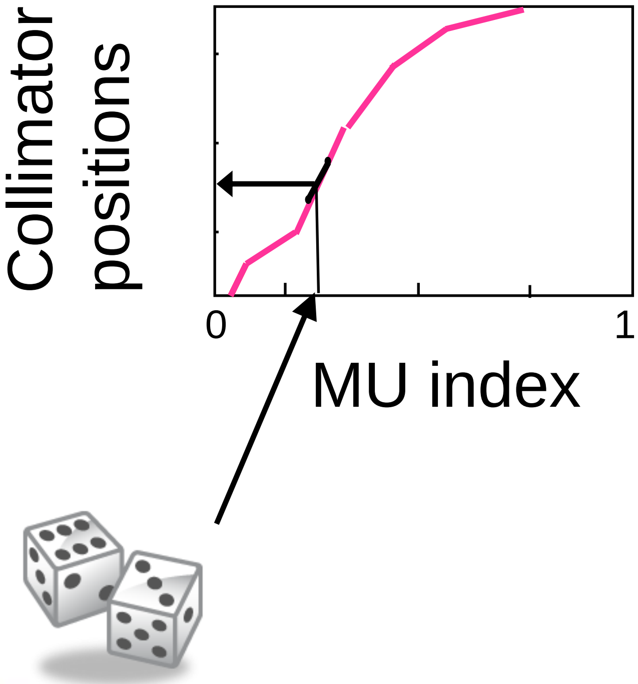
<u>Requirements:</u>

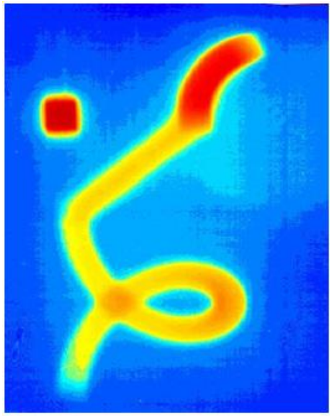
- Delivery log files
- Synchronization with respiratory trace

Jensen et al, Phys. Med. Biol. 57, 2012

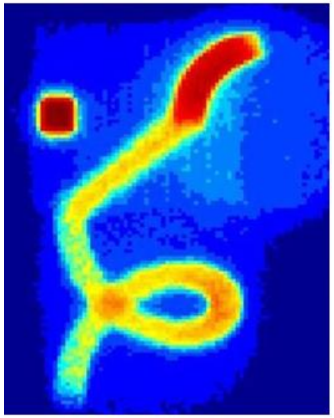
Position probability sampling approach

- Sample geometry for each incident particle from cumulative probability distributions
- Synchronization of beam and patient states requires ‘time stamping’ incident particles





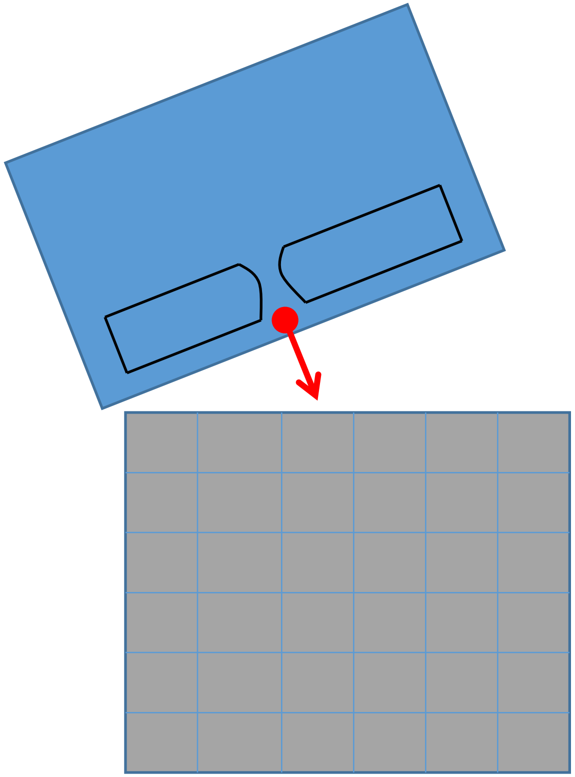
Film



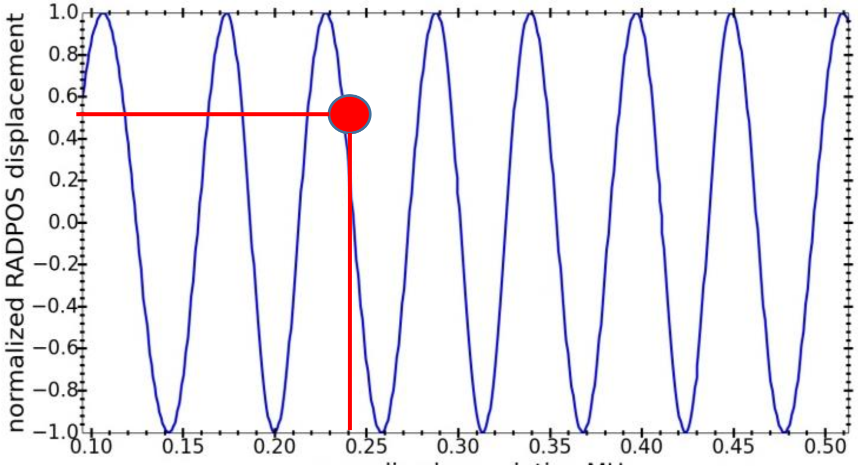
BEAMnrc/DOSXYZnrc Source 20

Courtesy of Tony Teke, BC Cancer Agency

4DMC simulation workflow

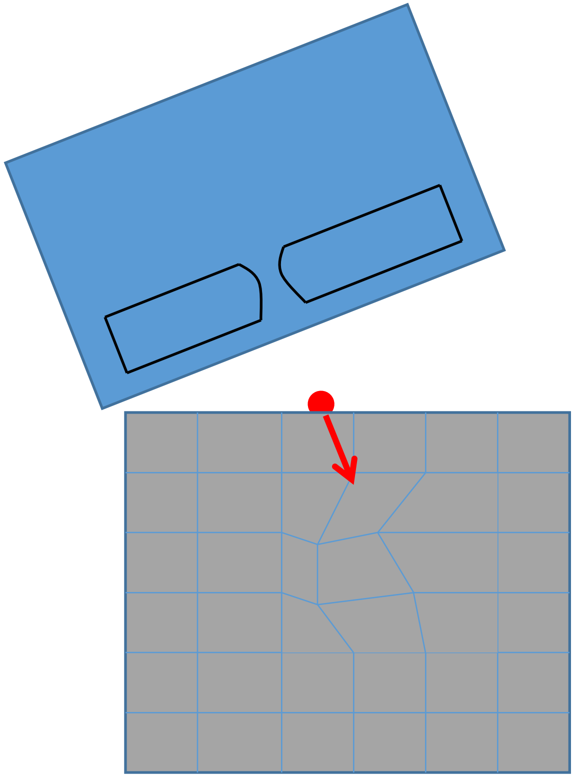


Sample respiratory state from motion trace synchronized to treatment delivery



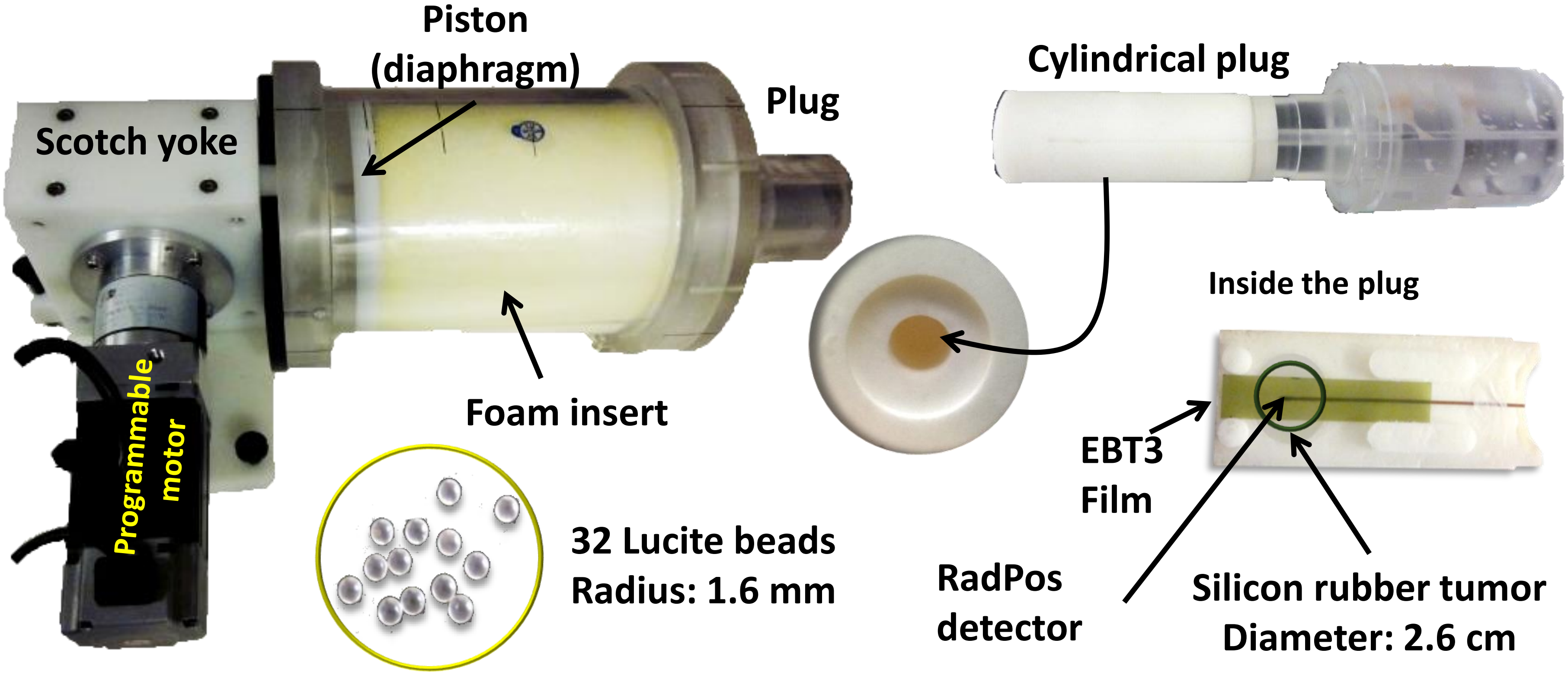
MU index

4DMC simulation workflow



- Look up deformations for current respiratory state
- Deform voxels and adjust density (mass is conserved)
- Transports particle through deformed dose grid and score energy deposition

Validation: Deformable lung phantom



Scotch yoke

Piston (diaphragm)

Plug

Cylindrical plug

Inside the plug

Programmable motor

Foam insert

32 Lucite beads
Radius: 1.6 mm

EBT3 Film

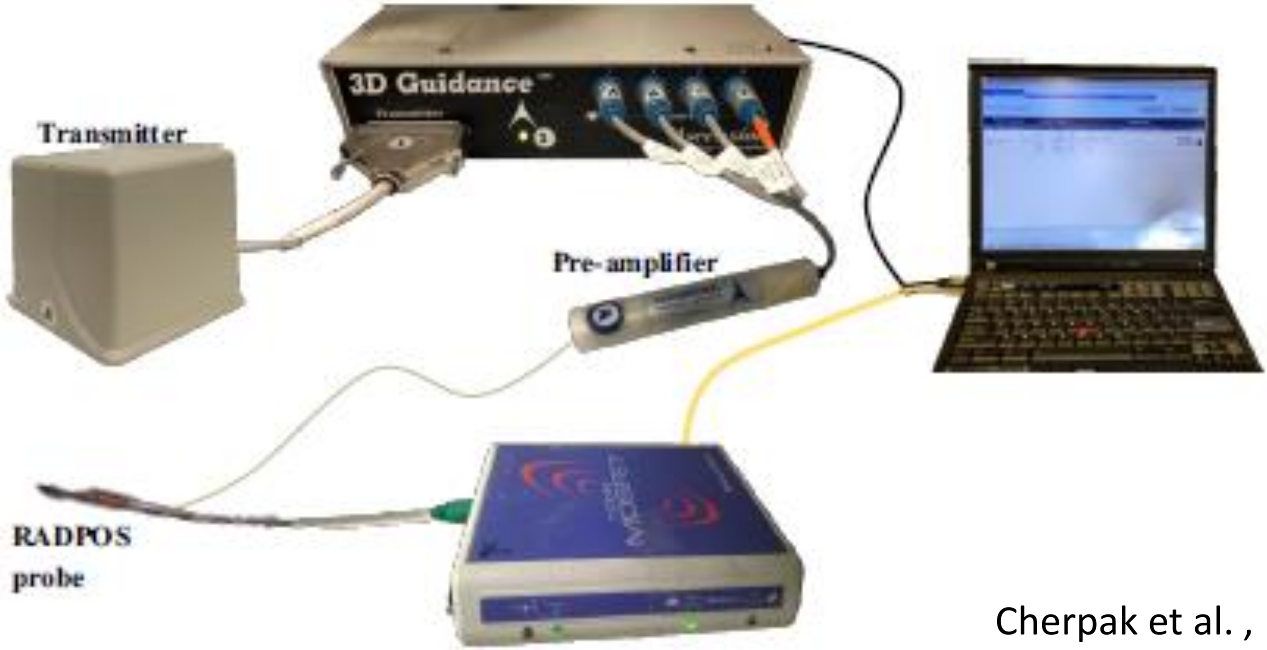
RadPos detector

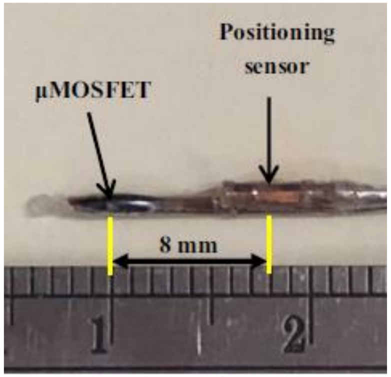
Silicon rubber tumor
Diameter: 2.6 cm

Gholampourkashi et al., European Journal of Medical Physics, 2020.

RadPos 4D dosimetry system

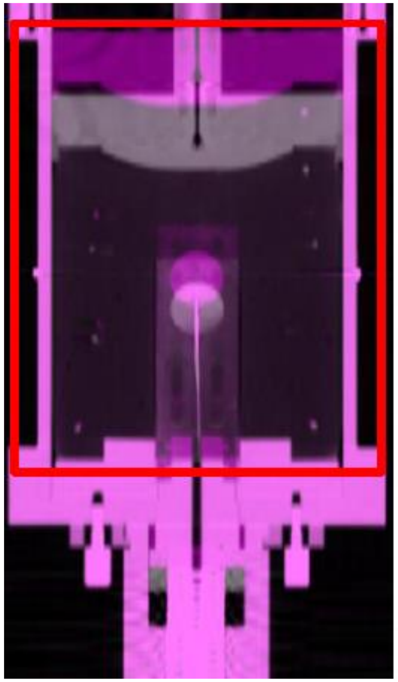
- Developed with Best Medical Canada
- Micro-mosfet detector + EM position sensor (10 Hz)



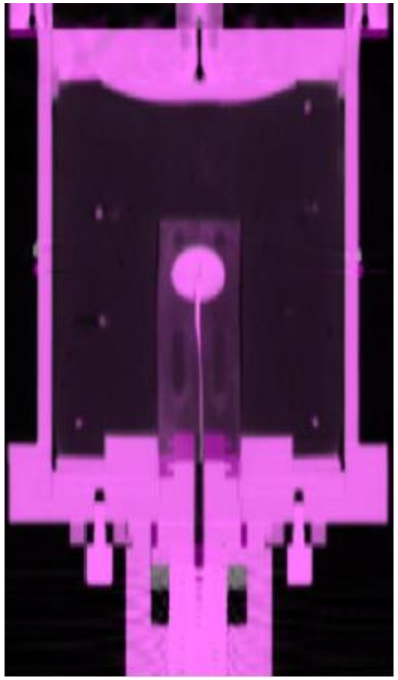


Cherpak et al. , Med. Phys. 36, 2009.

Deformable image registration



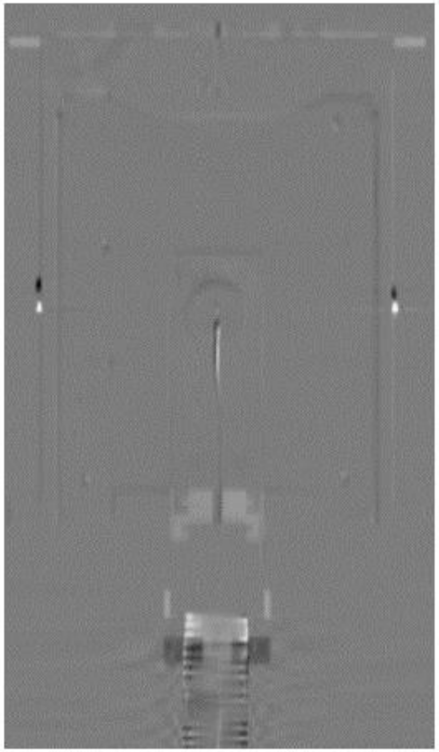
Before registration



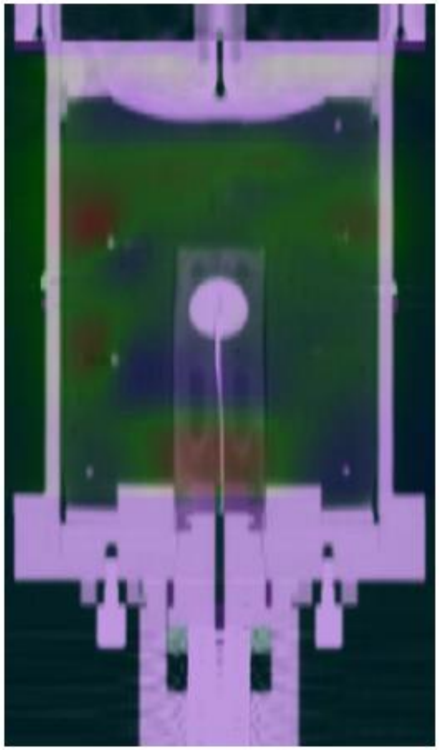
After registration

- Registered CT images of phantom in uncompressed and compressed states
- Velocity AI 3.2.0 (Varian Medical Systems) structure-guided multi-pass registration algorithm
- Tumour and beads used to guide DIR

DIR accuracy assessment



Deformed - Target



Jacobian map (local volume changes)

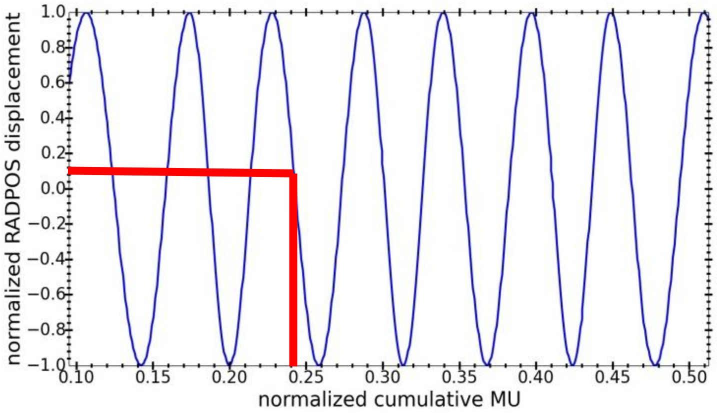
Registration Error (mm) assessed from beads

A/P	0.5 ± 0.3
L/R	0.4 ± 0.3
S/I	0.8 ± 0.5
3D	1.2 ± 0.4

Deformation vectors must be continuous!

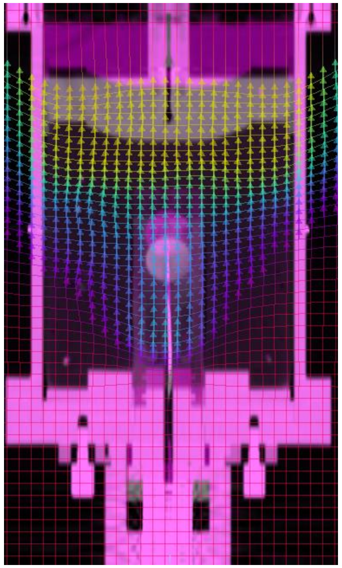
Motion modeling

MU Index determines a displacement vector scaling factor based on normalized motion trace



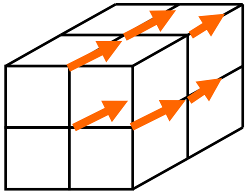
Normalized RADPOS trace

×



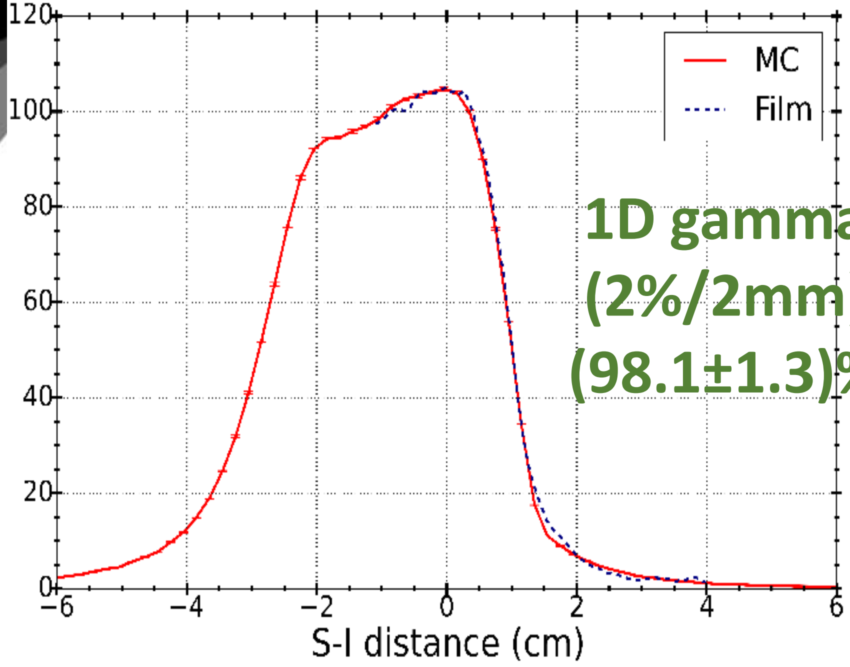
Exhale-Inhale Deformation vectors

=

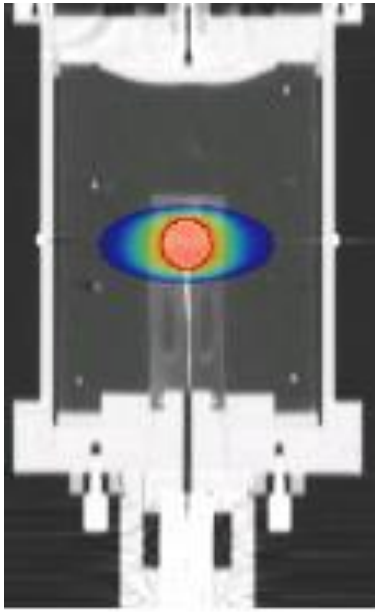


Scaled vectors applied to voxel

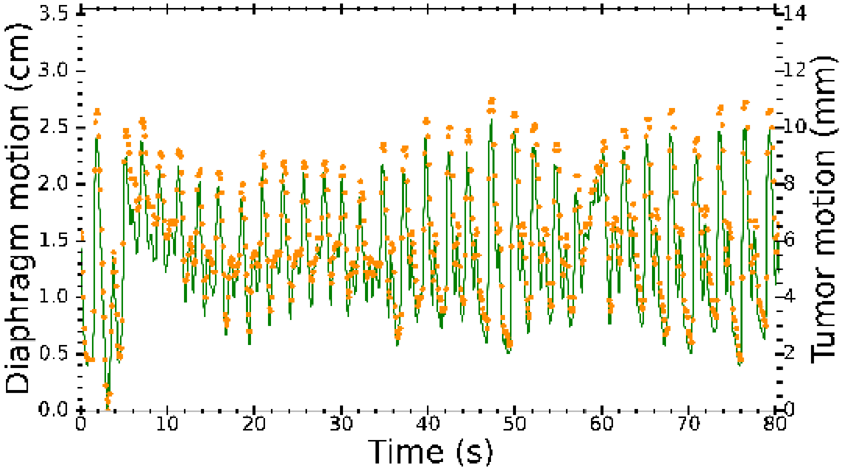
Experimental validation – VMAT plan



1D gamma (2%/2mm) (98.1±1.3)%



Planned dose distribution (Monaco)



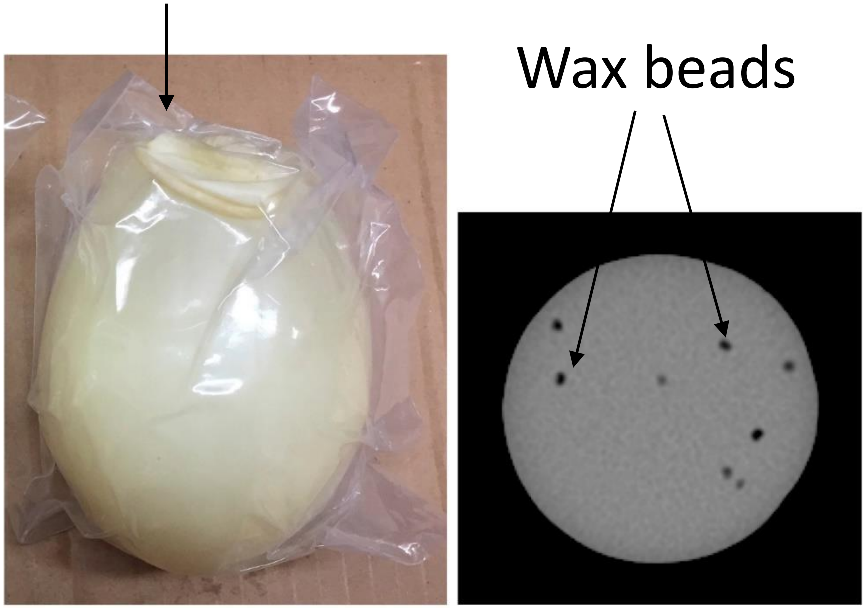
	MC (± 0.4%)	Film (± 2.3%)	RADPOS (± 2.4%)
1	104.3 cGy	104.5 cGy	104.3 cGy
2	102.0 cGy	102.6 cGy	101.2 cGy
3	101.0 cGy	103.0 cGy	100.0 cGy

Deformable gel dosimeter

Polymer gel dosimeter read out with x-ray CT

Vacuum-sealed LDPE bag

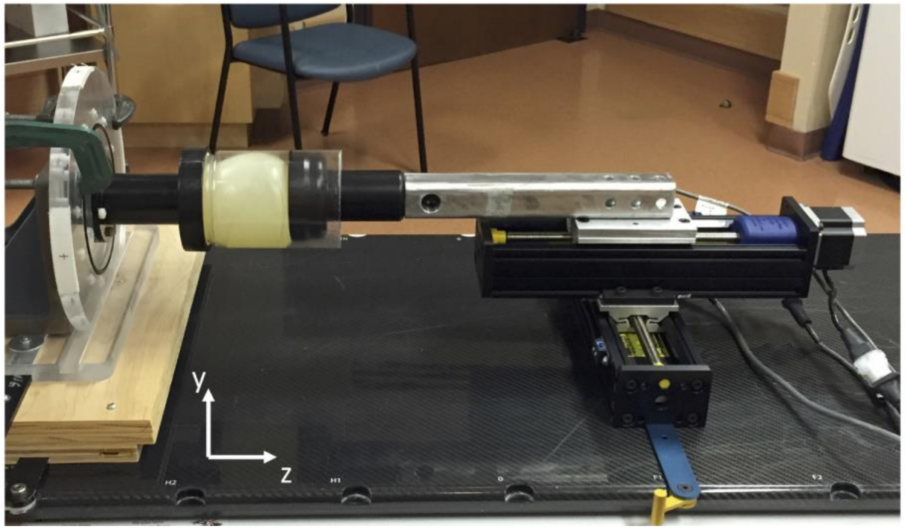
Wax beads



(a) (b)

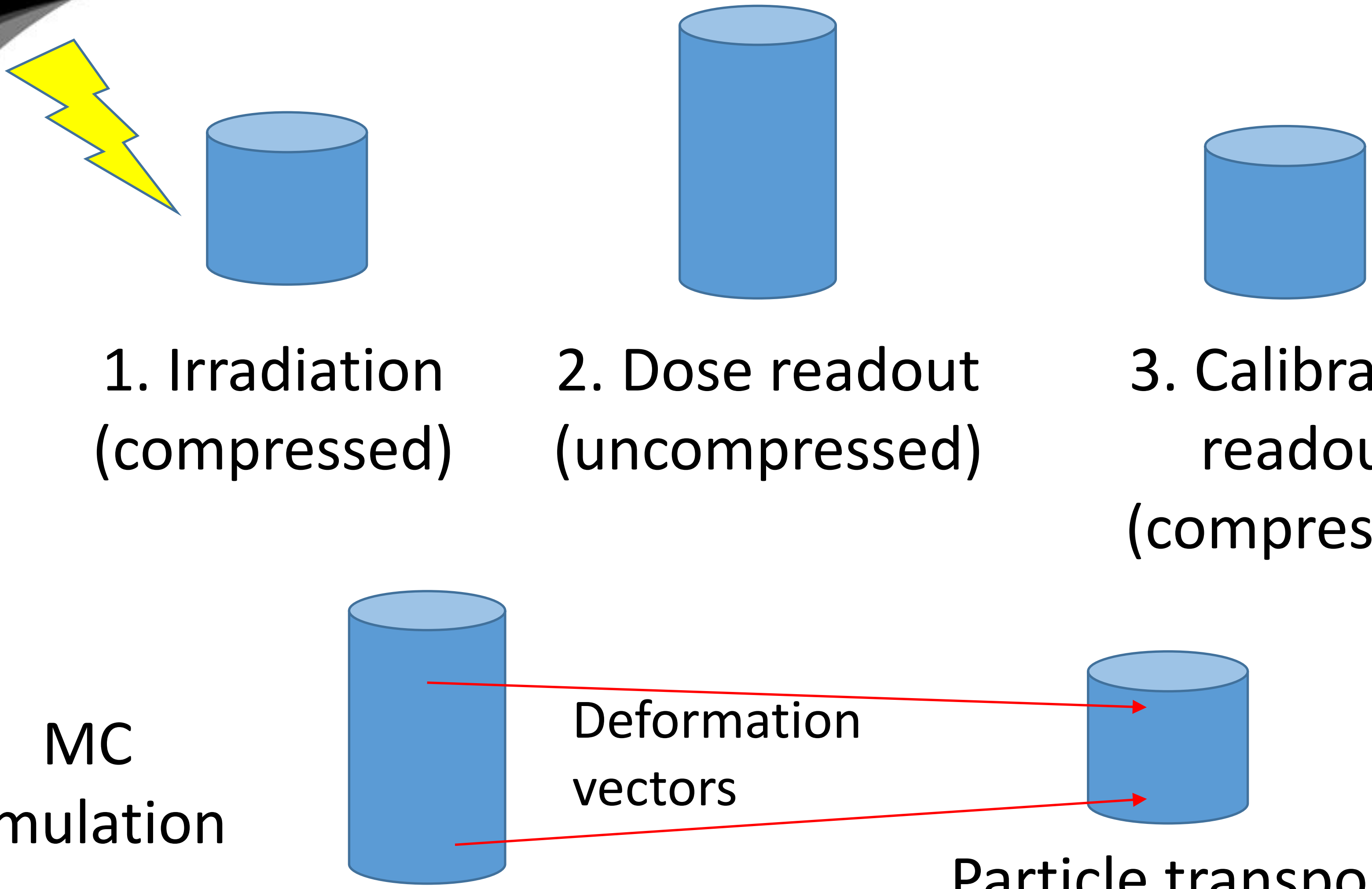
Maynard et al., Phys. Med. Biol. 63, 2018

Piston + stepper motor for gel compression



Maynard et al., Biomed. Phys. Eng. Express 6, 2020.

Experiment and simulations



1. Irradiation (compressed)

2. Dose readout (uncompressed)

3. Calibration readout (compressed)

MC simulation

Deformation vectors

Reference (uncompressed)

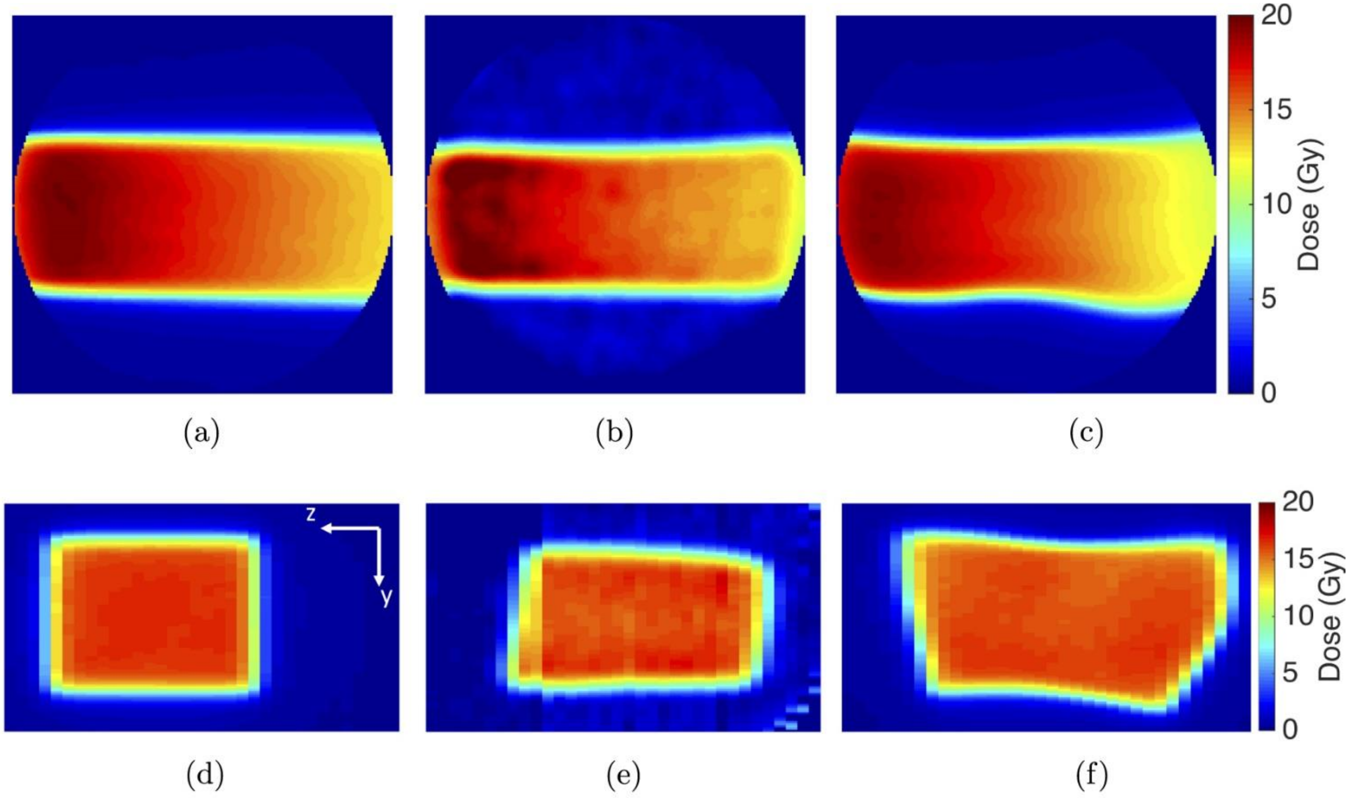
Particle transport (compressed)

Results: Gel vs. Simulations

TPS
(compressed)

Measured
(uncompressed)

defDOSXYZ
(uncompressed)



(a) (b) (c)

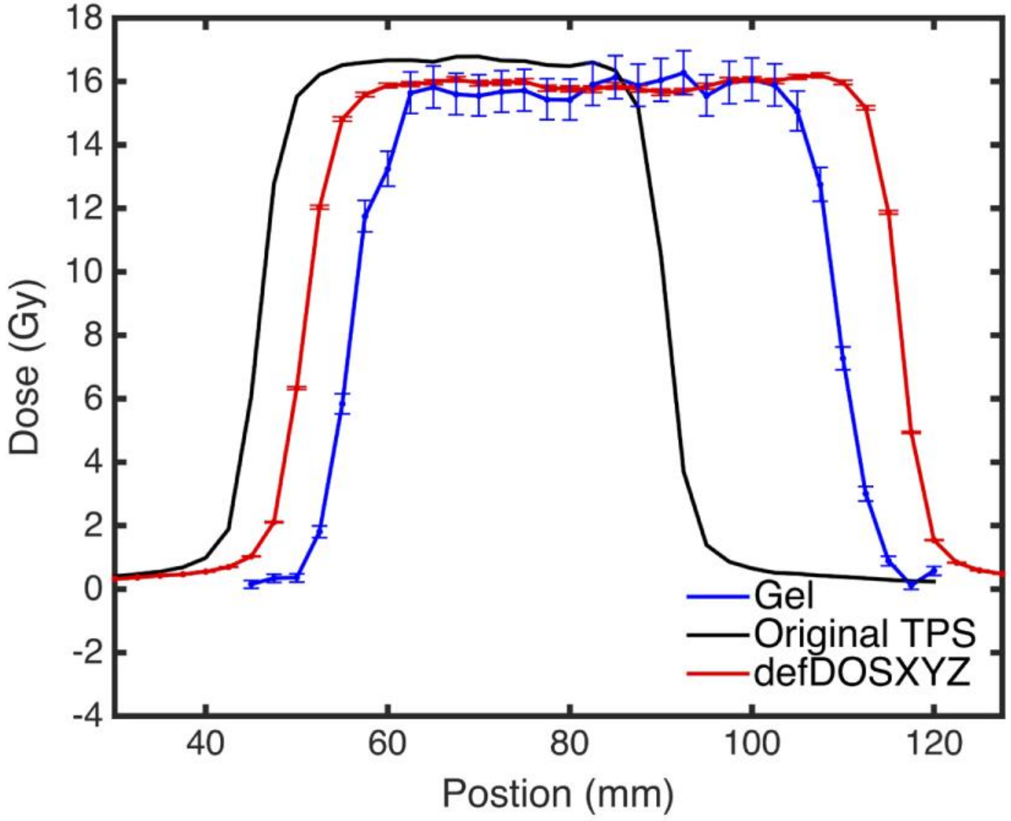
(d) (e) (f)

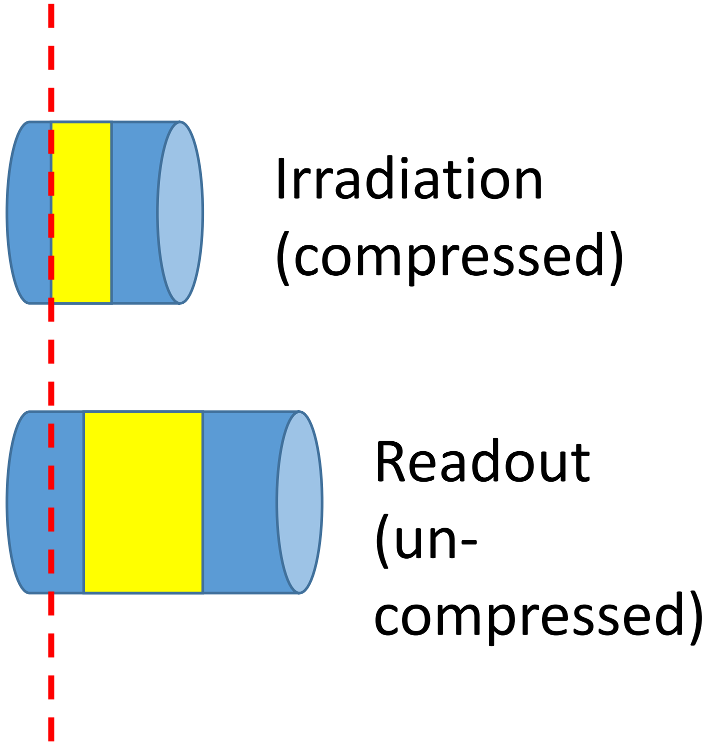
Transverse view
(XY)

Sagittal view
(ZY)

Maynard et al., Biomed. Phys. Eng. Express 6, 2020.

Dose profiles along Z (compression)

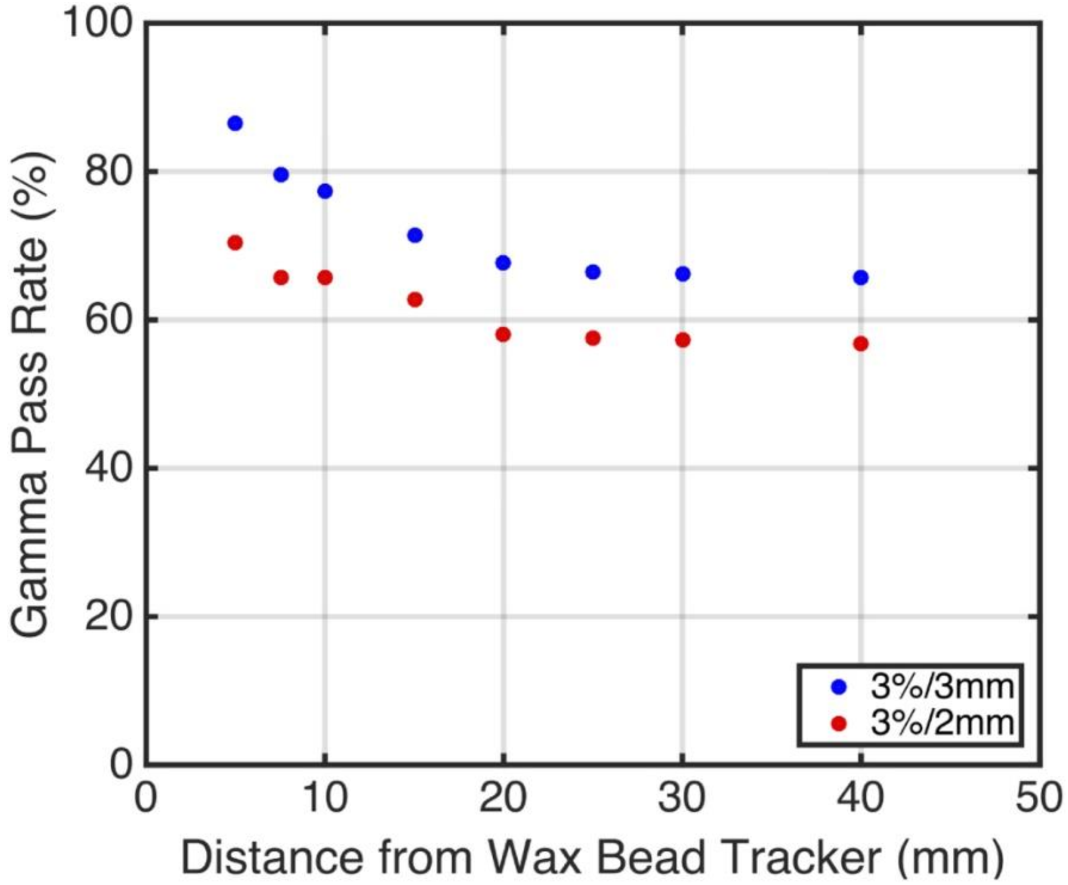




Maynard et al., Biomed. Phys. Eng. Express 6, 2020.

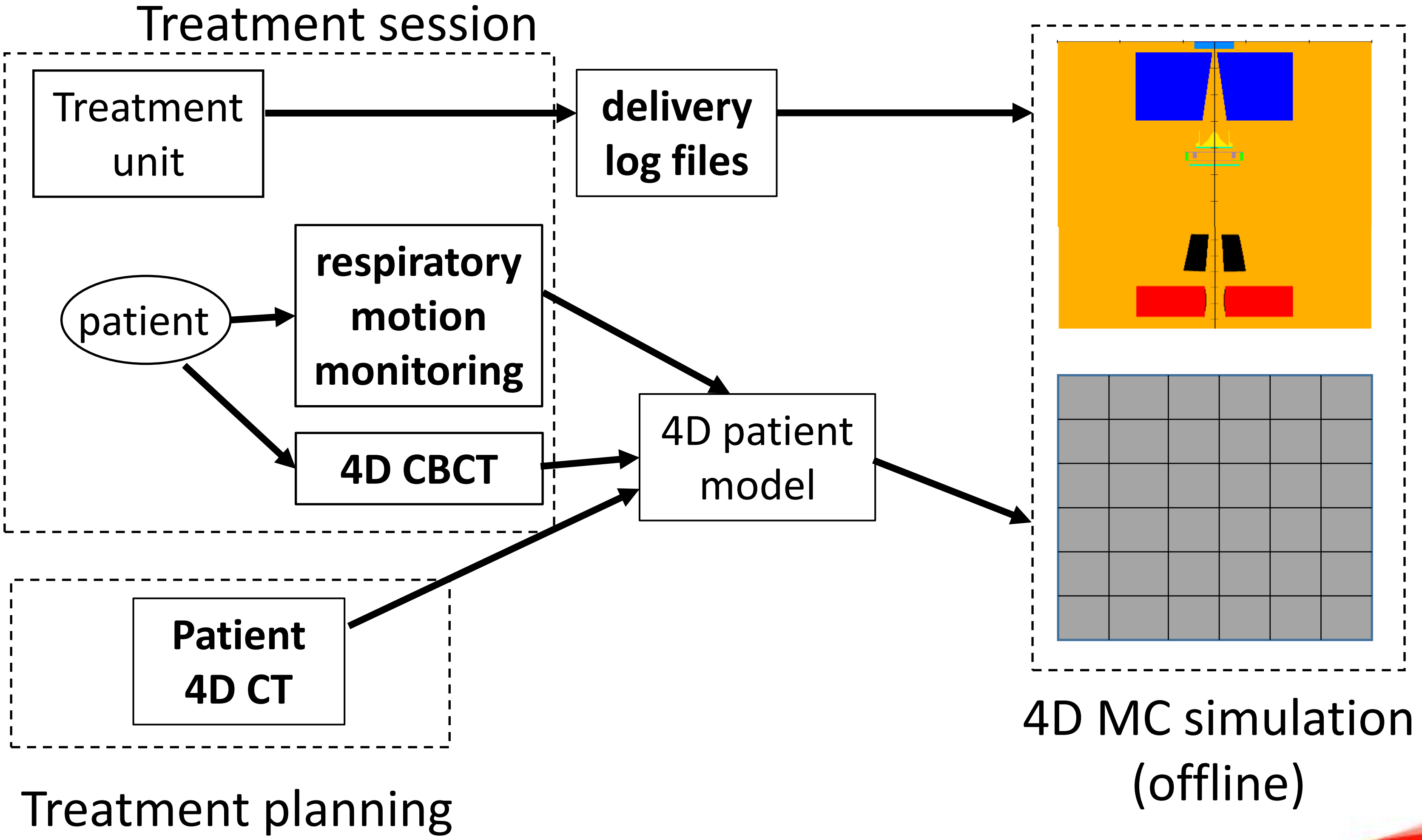
Better agreement close to wax beads

Average TRE from wax beads = 1.1 ± 0.6 mm



- test different DIR algorithms?
- more experiments needed (N>1)

Future work: patient dose reconstruction



Treatment session

Treatment unit

delivery log files

patient

respiratory motion monitoring

4D CBCT

4D patient model

Patient 4D CT

Treatment planning

4D MC simulation (offline)

Needs/Challenges

- 3D deformable dosimeters are desirable for validation of 4DMC simulations
- Need to be able to measure motion as well as dose
- Verification of patient dose reconstruction – role for in-vivo dosimetry?

Acknowledgements

- Gel dosimetry: M. Hilts and A. Jirasek (UBC Okanagan)
- RADPOS: J. Cygler (Ottawa Hospital Cancer Centre)
- BC Cancer Agency: T. Popescu and T. Teke
- Students: S. Gholampourkashi (Carleton) and E. Maynard (University of Victoria)
- Funding:

NSERC
CRSNG

OCAIRO

Thank-you!

Carleton **L**aboratory
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Physics