JULY 12–16 2020 VIRTUAL
JOINT AAPM | COMP MEETING
EASTERN TIME [GMT-4]

Development of 4DCT-MR based numerical lung phantoms for 4D radiotherapy and imaging investigations

A. DUETSCHLER[1,2], M. KRIEGER[1,2], D. C. WEBER[1,3,4], A. J. LOMAX[1,2] and Y. ZHANG[1]
[1]Center for Proton Therapy, Paul Scherrer Institute, 5232 Villigen PSI
[2]Department of Physics, ETH Zürich, 8092 Zürich
[3]Deparment of Radiation Oncology, University Hospital of Zürich, 8091 Zürich
[4]Department of Radiation Oncology, Inselspital, 3010 Bern

PAUL SCHERRER INSTITUT

INTRODUCTION

The effects of motion on radiotherapy are very complex and therefore numerical motion phantoms are widely used. Possible applications include:

- study the effect of motion on planned dose distributions,
- simulate motion mitigation techniques (rescanning, gating and tracking),
- development of new 4D planning strategies or 4D dose calculations,
- simulate online image guidance (surface motion, digitally reconstructed radiographs or cine MRI),
- deformable image registration (DIR) performance validation.

AIM

We have developed realistic 4D numerical lung CT phantoms to provide comprehensive 'ground truth' anatomical motion data for imaging and radiotherapy applications and simulations.

METHOD

Our approach is based on real patient image data, thus providing more realistic representations of tissue heterogeneity for more accurate dose calculation and more realistic image guidance.
The 4DCT-MRI phantom is based on

- CT data from 10 lung cancer patients
- deformed according to motion extracted from 5 volunteer 4DMRIs.

The workflow for the generation of 4DCT-MRIs based on a CT and 4DMRI is depicted in Figure 1.

1) DIR of 4DMRI to reference MRI state.
2) DIR of binary lung masks and application of deformation vector field (DVF) to lung mesh to establish inter-subject correspondence.
3) Application of 4DMRI DVF to corresponding CT points and warping of CT resulting in 4DCT-MRI.

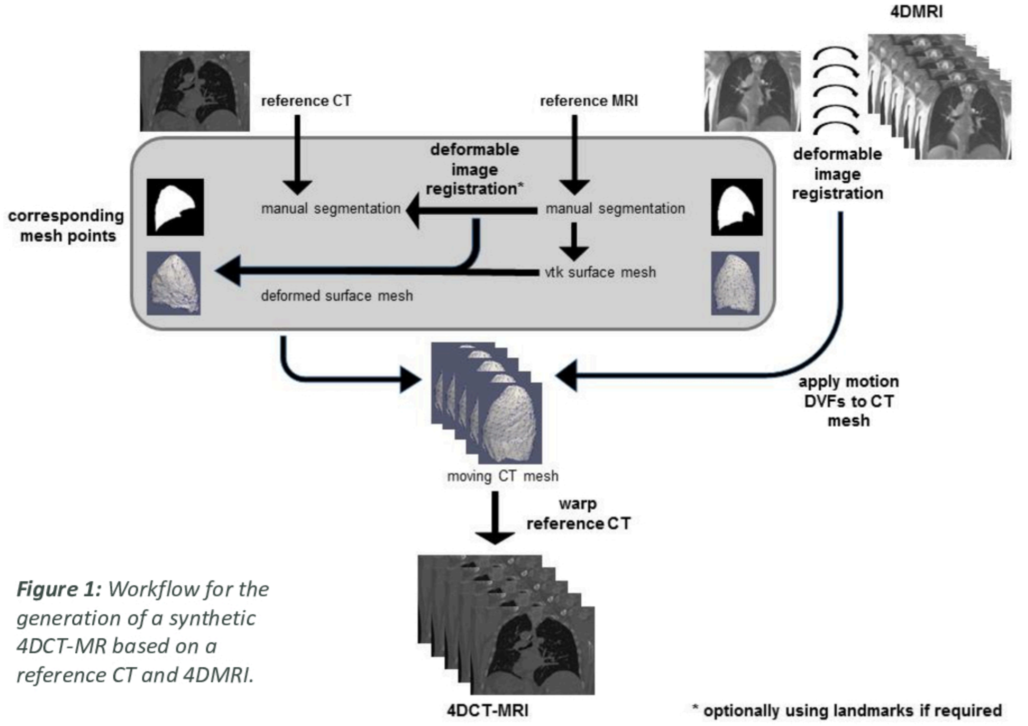


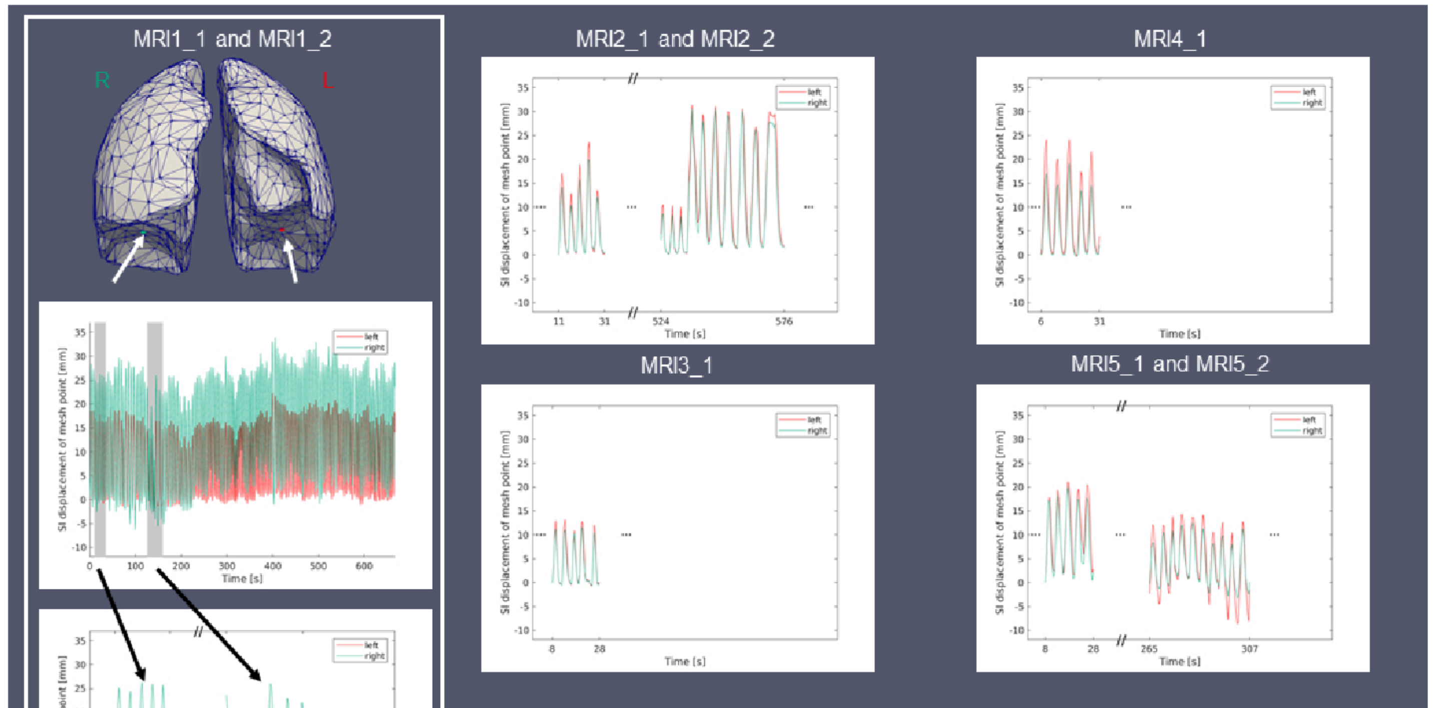
Figure 1: Workflow for the generation of a synthetic 4DCT-MR based on a reference CT and 4DMRI.

RESULTS

- Variety of anatomical scenarios based on 10 lung cancer CTs with pronounced differences in lung volumes/shapes and tumor locations/sizes (see Figure 3).
- 8 deformable motion patterns, each consisting of 50-100 individual motion phases, extracted from the 4DMRI data (see Figure 2).

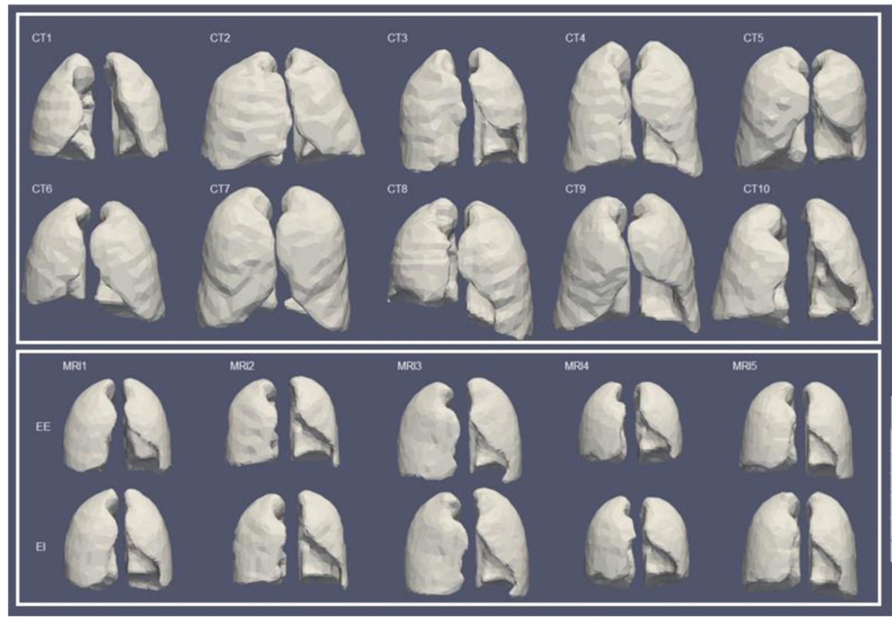
→ 80 simulated 4DCT data sets.

In Figure 4 a slice of the reference end exhale CT (CT1) together with an end inhale 4DCT-MRI slice is shown.



	MRI1_1	MRI1_2	MRI2_1	MRI2_2	MRI3_1	MRI4_1	MRI5_1	MRI5_2	Mean
Average amplitude L [mm]	17.2 ± 0.8	12.8 ± 4.8	16.9 ± 4.4	21.9 ± 9.4	12.8 ± 0.8	21.4 ± 2.8	17.3 ± 1.8	15.7 ± 2.6	17.2 ± 5.8
Average amplitude R [mm]	26.3 ± 0.8	21.5 ± 6.7	14.0 ± 3.7	21.1 ± 9.8	11.4 ± 0.5	15.9 ± 2.3	16.6 ± 1.7	11.2 ± 1.5	17.2 ± 7.1
Average period L [s]	4.6 ± 0.2	4.6 ± 1.7	3.8 ± 0.4	5.2 ± 1.6	.2.1941	4.9 ± 0.3	4.0 ± 0.4	4.2 ± 0.4	4.5 ± 1.1
Average period R [s]	4.6 ± 0.2	4.6 ± 1.7	3.8 ± 0.2	5.3 ± 1.8	3.9 ± 1.2	4.9 ± 0.3	4.0 ± 0.3	4.2 ± 0.4	4.5 ± 1.1

Figure 2: 4DMRI motion and statistics. For each of the 4DMRI geometries, a point in the dome of each half of the lung was selected (see top left for MRI1) and the superior-inferior (SI) motion is plotted. For each 4DMRI five breathing cycles following the reference EE phase were chosen to generate the synthetic 4DCT. For MRI1, MRI2 and MRI5 a few additional cycles, which show large motion irregularities, were also used.



	Lung volume L [ml]	Lung volume R [ml]
CT1 (EE)	1470	1744
CT2 (EE)	2292	2779
CT3 (EE)	1374	1885
Mean EE	1712 ± 412	2136 ± 458
CT4 (DIBH)	2097	2255
CT5 (DIBH)	1968	2849
CT6 (DIBH)	2147	1747
CT7 (DIBH)	2983	3525
CT8 (DIBH)	3108	2260
CT9 (DIBH)	2499	3005
CT10 (DIBH)	2279	2885
Mean DIBH	2440 ± 413	2646 ±549

	Lung volume EE L [ml]	Lung volume EE R [ml]	Lung volume EI L [ml]	Lung volume EI R [ml]
MRI1	1787	1980	1808	2197
MRI2	1252	1658	1474	1912
MRI3	1735	2162	1889	2342
MRI4	1291	1446	1612	1795
MRI5	1885	2153	2134	2440
Mean	1590 ± 265	1880 ± 283	1783 ± 228	2137 ± 247

Figure 3: Top: CT geometries from 10 patients. CT1-CT3 are end exhale (EE) reference CTs extracted from 4DCTs, whereas CT4-CT10 were acquired during deep inspiration breath hold (DIBH). Bottom: MRI lung geometries from 5 volunteers at end exhale (EE) and end inhale (EI) reference phases from the 4DMRIs. The corresponding volumes of the segmented lungs (left and right separately) are listed in the tables.

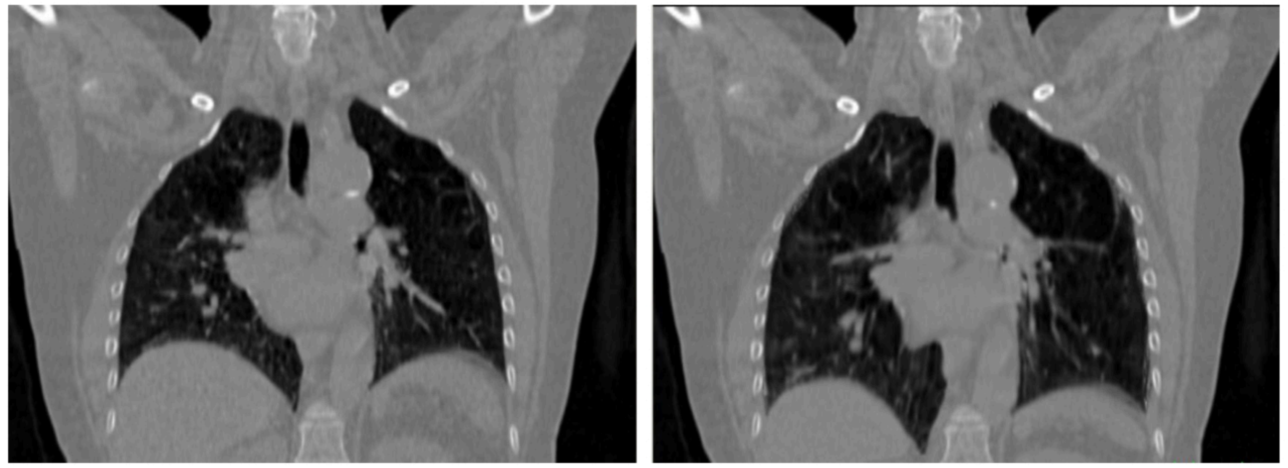


Figure 4: Left: reference CT slice (CT1). Right: end inhale slice of the 4DCT-MRI (using motion MRI1_1).

CONCLUSIONS

- The developed 4DCT-MR based numerical phantoms provide a realistic representation of a large selection of anatomical and motion scenarios.
- The motion vectors used to warp the CTs can be considered as the 'ground-truth' motion for each phantom, providing invaluable information for testing 4D imaging and motion modelling scenarios.
- The phantoms build an important foundation for further developments in 4D treatment planning and optimization, as well as for evaluation of novel image guidance for both proton and photon radiation therapies.
- Furthermore, we plan to extend the method to other organs in the thorax/abdomen region and incorporate more comprehensive shape and motion models into the platform, in order to expand the variability of both motion and patient anatomy.

ACKNOWLEDGEMENTS

This project is funded by Krebsliga Schweiz (KFS-4517-08-2018).

CONTACT INFORMATION

Alisha Duetschler, PhD student, Center for Proton Therapy, Paul Scherrer Institute
Email: alisha.duetschler@psi.ch