Four-Dimensional Dose Reconstruction for the Evaluation of Pulmonary Fluid–Induced Treatment Replanning

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PURPOSE

- Pulmonary edema induces substantial mass changes in the lungs and necessitates treatment replanning.
- Treatment replanning relies on the cumulative dose, which can be calculated using deformable dose accumulation (DDA).
- However, mass changes compromise deformable image registration and dose mapping, making their evaluation more challenging.
- The principle of energy conservation (PEC) has been used as an effective evaluation metric[1] but is limited in scenarios that involve substantial mass changes.
- This study aims to develop a four-dimensional (4D) dose calculation method that restores the validity of PEC for the objective evaluation of dose mapping accuracy,
  - two PEC-based error metrics will be introduced.
- These metrics may serve as a valuable quality assurance tool for adaptive radiotherapy and cancer retreatment.

MATERIALS & METHODS

- The 4D dose calculation begins with deformable image registration (DIR) from the replanning CT to the initial CT.
- DIR was performed using multi-modality (MM) and contour-consistency (CC) registration algorithms in MIM Software, and two hybrid algorithms (FEM-MM and FEM-CC) implemented in an in-house software program.
  - FEM-MM(CC) shares the same boundary displacements as MIM-MM(CC) but revises its interior displacements within each organ.
- A forward energy-mass mapping approach was applied to transfer the deposited energy/mass to the replanning CT,
  - DIR was performed from the replanning CT to the initial planning CT
  - Energy and mass were mapped from the initial planning CT to the replanning CT
- The four-dimensional (4D) dose at each voxel on the replanning image was defined as the ratio of the total transferred energy to the average transferred mass.
- Deposited energy was integrated on each image and summed to obtain a reference value for each organ.
- Dose error was defined as the relative energy loss (REL) represented by the difference between transferred and deposited energy and normalized by the average organ mass.
- The 4D dose calculation and verification framework was applied to a lung cancer patient whose pulmonary edema was present in the left lung in the initial planning CT but resolved on the replanning CT.

RESULTS

- The initial and retreatment plans were developed in Monaco with their doses illustrated in Figure 1 (a) and (b), where substantial mass changes are observed between the two scans.

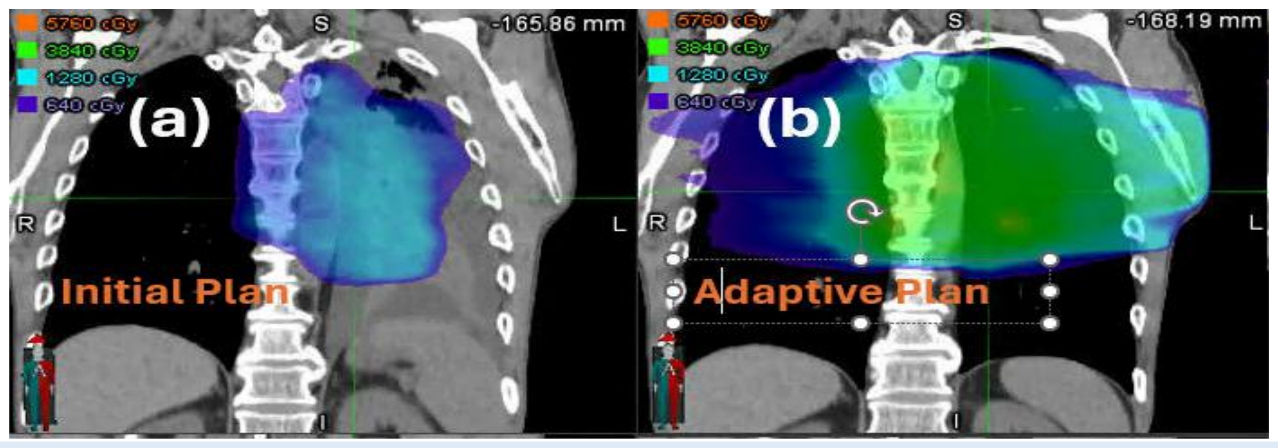

Figure 1. Coronal slices of a lung cancer patient showing (a) pulmonary edema and (b) liquid absorption.

- DIR was performed using the MIM-MM, MIM-CC, FEM-MM and FEM-CC algorithms, respectively.
- The uncertainties of these registrations were illustrated by
  - the target contour (green) and the deformed source contour (red & blue) in the diagram region (Fig 2b)
  - Jacobian determinant maps in the left lung show hot spots for MIM-MM(Figure 2c) and cold spots for MIM-CC (Figure 2d).

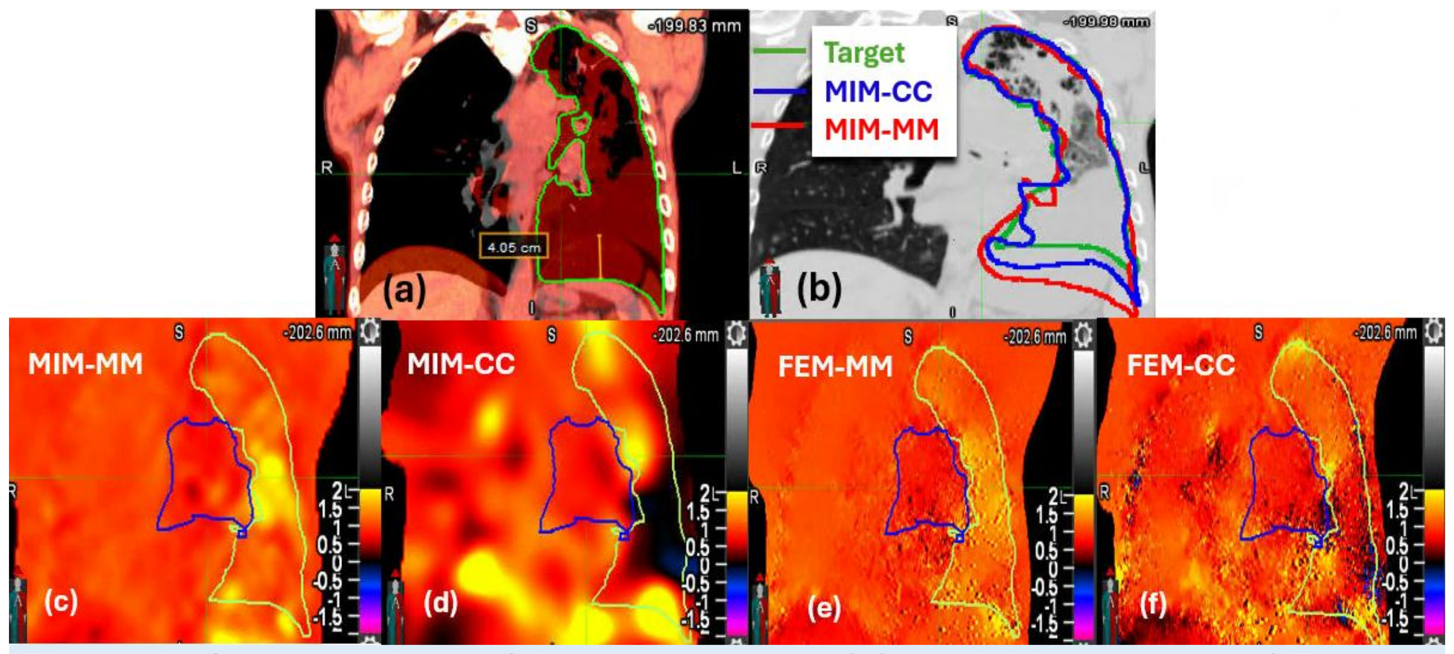

Figure 2. Coronal slices of the lung patient: (a) the initial planning CT rigidly registered to the replanning CT, (b) the initial planning CT overlaid with the contours deformed by the MIM-CC and MIM-MM algorithms; (c) and (d) Jacobian determinants of the MIM-MM and MIM-CC registrations; (e) and (f)Jacobian determinants of the FEM-MM and FEM-CC registrations.

- The hot and cold spots from the MIM registrations were corrected by the FEM methods as shown in Figure 2e and 2f.
- The four DIR algorithms showed mean distance-to-agreements (MDA) values close to the 3-mm tolerance (TG 132) for most OARs except the left lung.
- The standard deviations of the Jacobian determinants (STD-JD) were below 0.3 for the MIM-MM and FEM-MM whereas those for the two CC algorithms exceeded 0.3.

Table 1. The measured MDA and STD-JD for the four DIR algorithms.

MDA (mm)	Lung_L	Lung_R	Heart	ITVn	Aver	STD-JD	Lung_L	Lung_R	Heart	ITVn	Aver
MIM-MM	6.8	0.68	2.32	0.03	2.46		0.31	0.12	0.22	0.2	0.21
FEM-MM	7.1	1.11	3.2	0.78	3.05		0.26	0.13	0.21	0.23	0.20
MIM-CC	5.21	1.84	2.09	1.05	2.55		0.84	0.53	0.53	0.33	0.55
FEM-CC	5.2	1.84	2.03	1.08	2.54		0.68	0.38	0.46	0.34	0.46

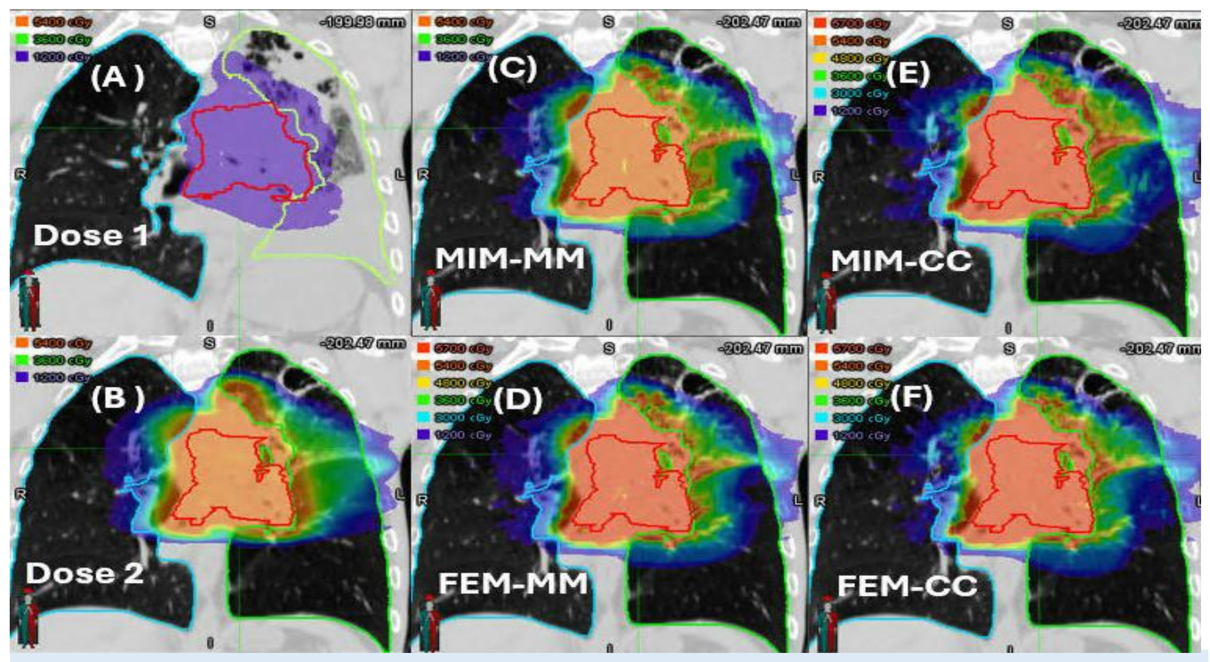

Figure 3. Radiation doses computed for the lung patient (A) the initial planned dose for 6 fractions, (B) the replanned dose for 24 fractions, (C-F) the 4D doses reconstructed with the MIM-MM, FEM-MM, MIM-CC and FEM-CC generated DVFs.

- With the derived DVFs, the forward energy-mass mapping method was employed to transfer deposited energy and mass.
- The reconstructed 4D doses on the replanning CT are shown in Figure 3 (C-F).
- The FEM algorithms reduced the STD-JDs, as shown in Figure 2 and Table 1, but their corresponding dosimetric improvements are still unknown.
- In contrast, the calculated 4D-dose is accompanied by the corresponding relative energy loss (EL) which represents the dose error for each OAR by the 4D dose definition (Table 2).
- It can be found that the FEM-MM based dose reconstruction shows the least energy loss in ITV (1.04%) among the four 4D dose reconstruction methods

Table 2. Example of water tank scan with W2 scintillator detector compared to Monaco with 1mm/2% criteria

	Lung_L		Lung_R		Heart		ITV	
	D_{mean} (cGy)	EL (%)	D_{mean} (cGy)	EL (%)	D_{mean} (cGy)	EL (%)	D_{mean} (cGy)	EL (%)
MIM-MM	1997	2.55%	981	4.17%	1419	1.32%	6264	1.37%
FEM-MM	1958	0.89%	963	4.88%	1413	1.31%	6289	1.04%
MIM-CC	2060	2.34%	1020	8.37%	1482	1.06%	6344	1.57%
FEM-CC	1970	1.74%	980	7.62%	1448	0.44%	6312	1.38%

CONCLUSIONS

- The 4D dose calculation takes account for mass changes and enables the deposited energy to serve as a gold standard for objective evaluation of underlying DIR errors and their dosimetry impact.
- The 4D dosimetry may help understand radiation dose variations in regions undergoing mass changes, thereby improving the accuracy of treatment replanning.

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