Potential dosimetric benefit of dose-warping based 4D planning compared to conventional 3D planning in liver stereotactic body radiotherapy (SBRT)

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Abstract. Respiratory motion induces dosimetric uncertainties for thoracic and abdominal cancer radiotherapy (RT) due to deforming and moving anatomy. This study investigates the extent of dosimetric differences between conventional 3D treatment planning and path-integrated 4D treatment planning in liver stereotactic body radiotherapy (SBRT). Respiratory-correlated 4DCT image sets with 10 phases were acquired for patients with liver tumours. Path-integrated 4D dose accumulation was performed using dose-warping techniques based on deformable image registration. Dose-volume histogram analysis demonstrated that the 3D planning approach overestimated doses to targets by up to 24% and underestimated dose to normal liver by ~4.5%, compared to the 4D planning methodology. Therefore, 4D planning has the potential to quantify such issues of under- and/or over-dosage and improve treatment accuracy.

1. Introduction

Stereotactic body radiotherapy (SBRT) for treatment of liver lesions, in principle, allows high dose conformity to the tumour with minimal dose to the normal tissue [1]. However, this is subject to the uncertainties introduced by delivering inherently inhomogeneous dose distributions to targets that deform and move due to patient respiration. Consequently, this could lead to reduced dose conformity and the potential for reduced tumour control. One approach for calculation of cumulative doses in moving and deforming targets (for inter- and intra-effects) is a 'dose-warping' technique [2-5]. In this study, we address the potential benefit of dose-warping based 4D treatment planning over conventional 3D for liver SBRT.

2. Materials and Methods

Two patients were chosen from a representative cohort of liver patients, representing opposite characteristics in terms of gross tumour volume (GTV) size and motion: a large GTV (54.5 cm^3) with small motion (7.5 mm) for patient A and a small GTV (6.7 cm^3) with large motion (16.6 mm) for patient B. Respiratory-correlated 4DCT image sets with 10 phases (0 – 90% of respiratory period)

were acquired. The internal target volume (ITV) was defined as the sum of tumour positions at exhale (50%) and inhale (0%) respiration phases, and a 5mm margin was added for generation of the planning target volume (PTV). The 3D conventional treatment planning with nine beam geometries for each of six fractions (normal clinical practice) was conducted using the 50% phase CT set as a reference image; it was then copied over to the other nine phases and recalculated. The path-integrated 4D dose accumulation was performed using a dose-warping technique based on an *optical flow* method [6, 7] of deformable image registration (DIR) which we have previously established to be the most accurate of the algorithms studied [5]. For all registrations, the 50% phase was the 'target' image, used as a reference to which the 'source' images of the other respiration phases were morphed. Doses of each source image were transformed using deformation vector fields (DVFs) calculated from each registration. These warped doses were equally weighted to estimate the path-integrated 4D-cumulative dose distribution. Target volume coverage as well as doses to other surrounding organs were evaluated with the 4D planning methodology and compared with those from the conventional 3D planning approach.

3. Results and Discussion

The results of DIR were assessed first by visual inspection of difference maps, to affirm that the registration was acceptable. An example of DIR from extreme inhale phase (source) to extreme exhale phase (target) is shown in figure 1. In the first row, the upper (red, short dash) and lower (green, long dash) dashed lines show the alignment of the liver and the kidneys, respectively, before and after DIR. In the second row, the difference map after DIR shows the difference between the target and the calculated image, illustrating the high performance of the optical flow method.

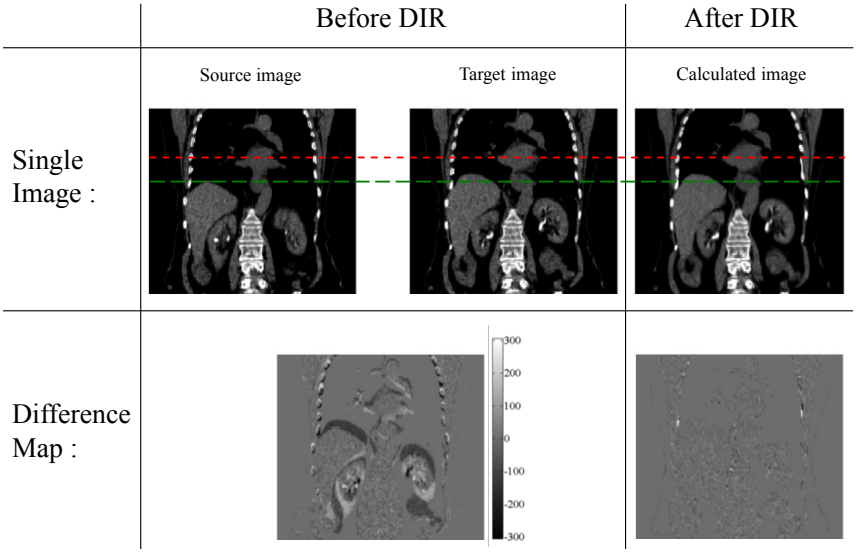


Figure 1: Example results of deformable image registration using the optical flow method are shown in the coronal view. The scale in the difference map is in HU.

Figure 2(a) and 2(b) depict dose-volume histograms (DVHs) of targets and normal liver for patients A and B, respectively. According to the dose prescriptions of the 3D-static plans, the D_{mean} of the PTV was 47.4 and 52.7 Gy for patient A and patient B, respectively. D_{mean} calculated from the 4D-cumulative plan was 2.2 and 3.8 % lower for patient A and patient B, respectively. The ratio of D_2 (2% near-maximum dose) / D_{98} (98% near-minimum dose), i.e. homogeneity indices (HI), were calculated

from DVHs. The HI difference between 3D and 4D plans was less than 1 % for GTV and ITV for both patients. In contrast, HI_{3D} for PTV decreased by 14.0% and 23.5% compared to HI_{4D} for patient A and patient B. These results illustrate that the 3D-static plan overestimated dose by up to ~24%, particularly at the high-dose region around the PTV margin, compared to the 4D-cumulative plan which represents a more accurate approximation of the doses actually delivered. These discrepancies were mainly introduced by circumstances in which the presence of dose gradient was most prominent in PTV margin (but out of the ITV). Another dominant factor yielding dosimetric differences between the two planning schemes is the fact that healthy liver tissue adjacent to the PTV could move in and out of the treatment beam field over the breathing cycle, resulting in undesired dose to healthy liver while reducing dose conformity to the PTV. As evidence of the latter point, it is worth to note that the smaller volume with larger motion yielded a greater discrepancy between 3D and 4D plan than the larger volume with smaller motion.

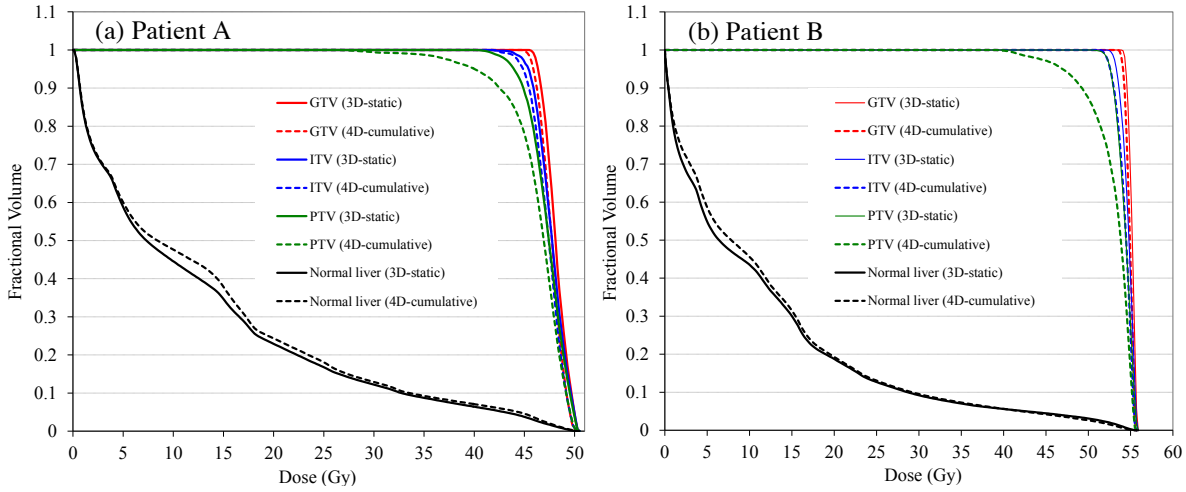
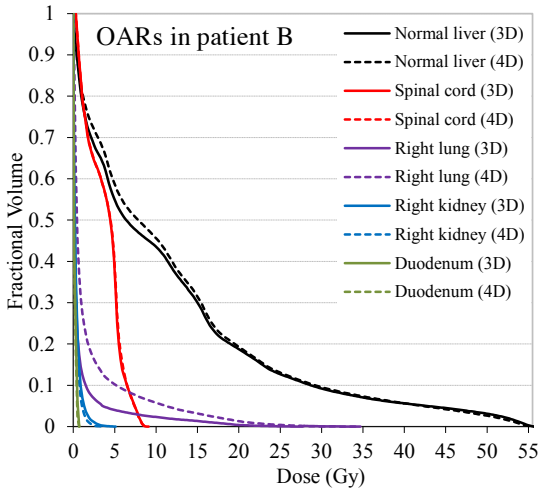


Figure 2: Dose-volume histograms (DVHs) for targets and normal liver: **(a)** patient A (large GTV with small motion) and **(b)** patient B (small GTV with large motion). Straight and dashed lines illustrate the results calculated from 3D-static and 4D-cumulative planning, respectively (red: GTV, blue: ITV, green PTV, and black: normal liver).

For normal liver, there is an observable trend such that the mean doses (D_{mean}) calculated from 3D-static planning were reduced by 4.3% and 4.7% compared to 4D-cumulative planning for patient A and B, respectively. This illustrates that 3D-static planning underestimates the delivered doses to healthy tissues. Doses to other organs are low and consequently differences between 3D and 4D methods are not as troubling in an absolute sense (see figure 3).

4. Conclusions

In this study, it is demonstrated that the typical 3D-planning approach appears to significantly underestimate dose to the PTV, while overestimating dose the surrounding healthy liver. The general consequence can thus be undesired reduction of dose conformity and tumour control. 4D-cumulative planning has, therefore, the potential to quantify such issues of under- and/or over-dosage and to benefit patient outcomes in radiotherapy treatment.



OARs	D_{mean} (3D / 4D)	D_2 (3D / 4D)	D_{98} (3D / 4D)
Normal liver	11.6 / 12.1	52.6 / 51.6	55.5 / 55.3
Spinal Cord	3.9 / 3.9	8.0 / 8.0	8.9 / 8.9
R Lung	1.0 / 2.0	11.3 / 18.0	27.7 / 34.7
R kidney	0.4 / 0.4	2.0 / 1.5	5.1 / 3.7
Duodenum	0.2 / 0.2	0.6 / 0.5	0.7 / 0.7

Figure 3: An example of dose-volume histograms (DVHs) for critical organs in patient B. Straight and dashed lines illustrate the results calculated from 3D-static and 4D-cumulative planning, respectively. The table shows the mean dose (D_{mean}), the 2% near-minimum dose (D_2), and the 98% near-maximum dose (D_{98}) in each organ for both planning schemes.

5. Acknowledgements

This work is supported by an RMIT University Research & Innovation Emerging Researcher Industry Award (Dr R Franich, Dr Taylor).

6. References

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