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Variable margin expansion to account for MR image distortion in treatment planning

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Introduction

- MR-based treatment planning, particularly with the MR-Linac, has become increasingly accessible. [1] [2]
- Despite proposed algorithms to correct MR geometric distortions, residual distortions still exist.
- The spine is the most common site of bony metastatic disease, seen in at least 40% of patients with advanced cancer (especially breast, lung, and prostate cancer). [3]
- In a previous study, we measured the residual distortions for MRL systems – they can reach up to 3 mm at 20 cm away from the imaging center. [4]
- MR residual distortions, although small, may have a great impact on treatment plans with a sharp dose gradient, such as spine radiosurgery (SRS) plans.
- To treat SRS patients with a 1.5T MR-Linac, it is necessary to assess the impact of MR residual distortions and develop a solution to mitigate this impact.
- We are the first to propose a variable margin expansion approach to account for such MR residual distortions in treatment planning.

Methods

Specific Aim 1

- Nine CT-based SRS treatment plans (prescribed to 18 or 24 Gy) with assumed underlying MR distortion were collected for this study. The SRS contouring was done in our clinic following the published contouring guideline from the International Spine Radiosurgery Consortium. [5]
- In our previous study, we created a mathematical model to describe MR residual distortions. [4]
  - We used two sets of independent geometric distortion data, represented by 3D vectors, measured by two different MRI vendors (Figure 1).
  - We trained a parametric second order polynomial model to represent the distortions as vectors at voxel level.
  - The model was validated using the two datasets with the maximum average simulation error of 1.4±1.8 mm, 0.3±0.3 mm, and 0.4±0.5 mm in the X, Y, and Z directions, respectively.
- To simulate MR scans with residual geometric distortions, we applied the distortion model to the CT images to generate distorted images using a distance transform method, with the center of the CT images as the origin. [6]
- The distortion vectors were applied to deform the GTV and cord/cauda contours to generate the presumably actual locations of the GTV and cord/cauda.

Aims

Specific aims:

1. Determine the variable margins at voxel level to account for MR residual distortion.
2. Develop a margin expansion algorithm to account for the variable margins.

Goal:
To reduce the impact of MR spatial distortions on the accuracy of MR-based treatment planning for MRL systems.

Long Term Goal:
To improve tumor control and reduce normal tissue toxicity in patients treated with MRL systems, thus improving their quality of life.

Methods

Specific Aim 2

- At the same time, we expanded the original GTV and cord/cauda contours using a variable margin expansion algorithm, developed in MATLAB.
  - The variable margin expansion operation is related to the curve deformation by the estimated distortion magnitude along the normal direction. [7]
  - It is based on the union of the original and deformed contours through differential mathematical morphology. [8]
- A new plan was reoptimized by using the expanded contours, while keeping planning parameters and other contours the same as the original plans.

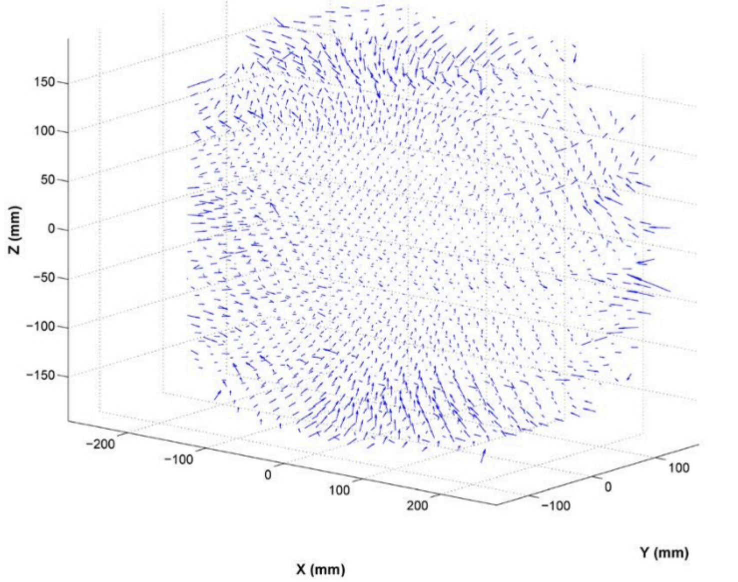

Figure 1. Quiver plot in 3D of the measured distortion data from two different MRI vendors.

Results

- Impact of MR distortions was case specific.
- Of the 9 plans, one plan had underdose to the target due to the distortion.
  - The GTV mean dose decreased from 25.1Gy to 23.9Gy.
- Four plans had increased cord/cauda maximum dose (6.2%, 8.6%, 12.2% and 22.7%).
  - One of these increased from 11.6 Gy to 14.2 Gy, resulting in significant overdose to the spinal cord.
- After reoptimization using the expanded contours, the GTV mean dose of that one plan increased to 24.2 Gy while keeping the same cord dose level.
- Also, the maximum cord dose of those four plans fell back towards the original clinical goals.

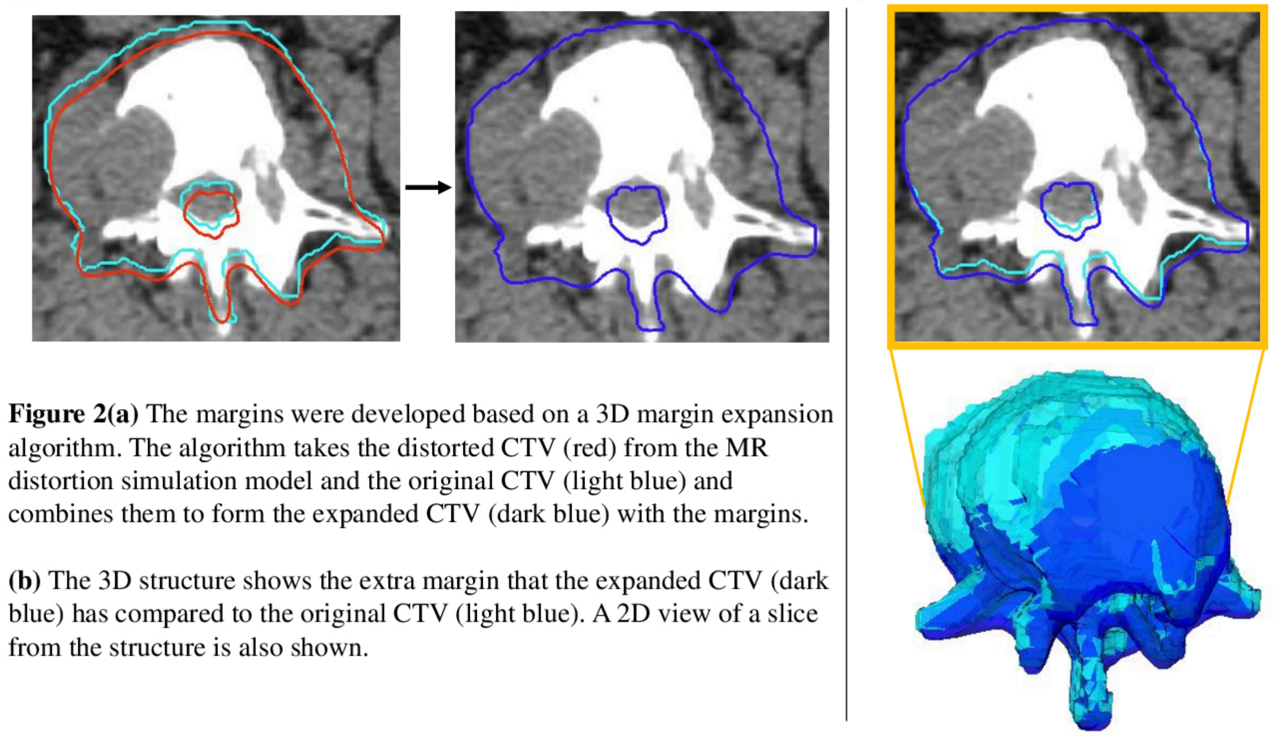

Figure 2(a) The margins were developed based on a 3D margin expansion algorithm. The algorithm takes the distorted CTV (red) from the MR distortion simulation model and the original CTV (light blue) and combines them to form the expanded CTV (dark blue) with the margins.

(b) The 3D structure shows the extra margin that the expanded CTV (dark blue) has compared to the original CTV (light blue). A 2D view of a slice from the structure is also shown.

GTV	Mean Dose (Gy)	Mean Dose (Gy) to Deformation	% change	Mean Dose (Gy) to Deformation After Reoptimization
1	25.0	24.8	-0.7	24.9
2	18.5	18.4	-0.3	18.4
3	19.0	18.9	-0.5	19.0
4	25.0	24.8	-1.0	25.1
5	25.1	23.9	-4.9	24.1
6	18.8	18.6	-0.7	18.8
7	24.7	24.7	-0.2	24.9
8	25.0	24.6	-1.4	24.8
9	25.0	24.9	-0.5	25.1

	Max Dose (Gy)	Max Dose (Gy) to Deformation	% change	Max Dose (Gy) to Deformation After Reoptimization
1	16.6	16.5	-0.1	15.8
2	12.0	12.7	6.2	11.3
3	15.2	16.5	8.5	15.4
4	11.6	14.2	22.7	12.9
5	16.4	14.0	-14.8	14.3
6	15.3	15.3	0.2	14.4
7	16.7	18.8	12.2	15.7
8	9.1	8.3	-8.8	8.6
9	10.0	9.1	-9.1	8.7

Table 1 All prescribed doses are either 18 or 24 Gy. In plan 5 for the GTV, distortion caused a significant percent decrease in mean dose: an underdose. After reoptimization, the mean dose returned to the prescription. In the 4 highlighted plans for the cord/cauda, distortion caused significant percent increases in maximum dose. After reoptimization, maximum doses fell back towards the original clinical goals.

Conclusions

- There are significant negative impacts to the tumor dose and normal tissue toxicities due to MR residual distortions when planning treatments for SRS patients with a 1.5T MR-Linac.
- We demonstrated a variable margin expansion approach to account for MR image distortion in SRS treatment planning.
- The approach should be implemented if SRS patients will be treated with MR-Linac.

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Acknowledgements

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