Simulating MRI Susceptibility-Induced Geometric Distortions for Cranial Stereotactic Radiotherapy Planning

Vivian Hughes[1,2], Tigris Joseph[1,3], Keith Wachowicz[4], Justin Oh[1], Ermias Gete[1,5], Steven Thomas[1,5], Andrew KH Robertson[1,5]

[1]Medical Physics Department, BC Cancer Vancouver, [2]Department of Physics, Engineering Physics, and Astronomy, Queen's University, [3]Department of Physics and Astronomy, University of British Colombia, [4]Department of Oncology, University of Alberta, [5]Department of Surgery, University of British Colombia

Introduction

- Magnetic resonance imaging (MRI) scanners are increasingly used for radiation therapy treatment simulation and planning**.**
- MR images can suffer from geometric distortions which are a critical concern in radiation treatment planning, as they can result in dose delivery errors[1].
- Differences in tissue susceptibility ($\Delta\chi$), such as interfaces between air and tissue, can lead to **patient-specific distortions.**
- Most prior work[2-4] has quantified the maximum signal shift in tissue but has not investigated clinically relevant contours or resulting RTP dose metrics. **To our knowledge, no prior research has focused on small cranial targets near air interfaces.**

Objective: Quantify and evaluate the dosimetric impact of susceptibility-induced MR geometric distortions in cranial targets for stereotactic radiotherapy cases near air-tissue interfaces.

Methods

- 19 stereotactic radiotherapy plans with targets close to air-tissue interfaces were identified: 9 brain metastases, 6 acoustic neuromas, 4 pituitary adenomas.
- Gadolinium-enhanced axial T1-weighted MPRAGE MRI was used for image acquisition.
- GTVs were contoured on structural MRI images acquired on a 1.5 T scanner, which were used to generate PTVs (labeled 'distorted'). The simulated readout gradient was 4 mT/m.
- The susceptibility-induced MR distortion (signal shift map) was derived using a fast Fourier transform convolution algorithm (pipeline in Figure 1).
- A linear-step numerical method estimated the undistorted GTV from the simulated shift map, and an undistorted isotropic PTV of 1 mm was generated.

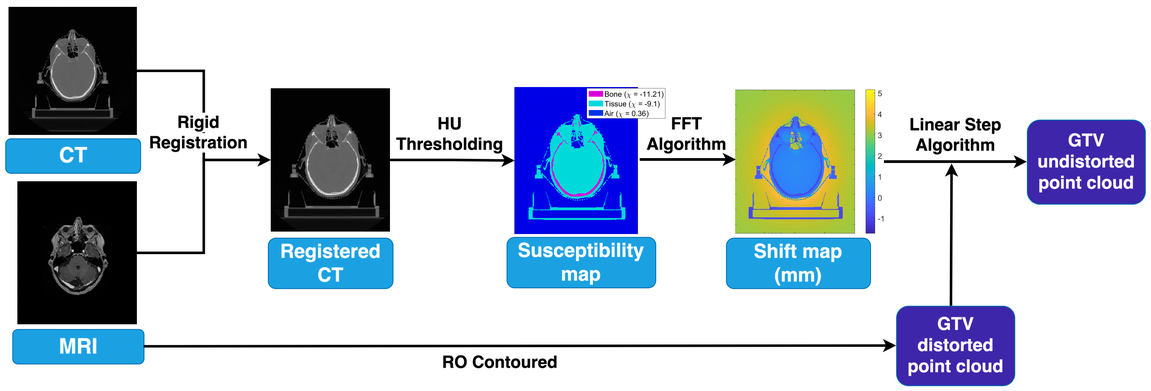

Figure 1: Image processing workflow: the CT image was rigidly registered to the MRI image, the CT image was used to create a susceptibility map, a fast Fourier transform (FFT) algorithm was then used to generate a signal shift map, and a linear step algorithm was used to undistort the GTV point cloud structure from the signal shift map.

- Figure 2 shows example distorted and undistorted PTV contours.
- **Geometric distortion analysis**: minimum (min), mean, and maximum (max) geometric distortion were extracted in distorted GTVs.
- **Dosimetric analysis**: change in dose (min, mean, max) and target coverage (volume receiving 95%-100% of prescribed dose) between the undistorted and distorted PTV/GTVs were calculated.

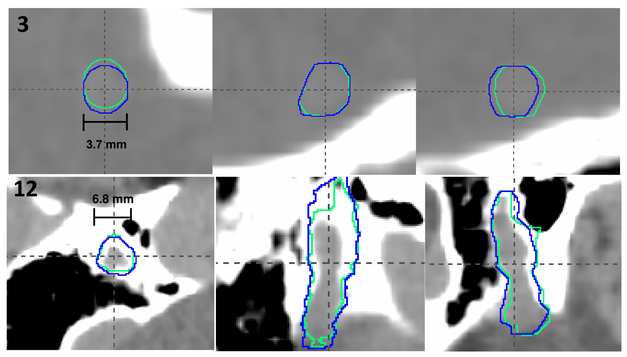

Figure 2: Axial, coronal, and sagittal CT images showing example distorted (blue) and undistorted (green) PTV contours for two patients.

Results: Distortion

- Table 1 includes the min, mean, and max shifts in the GTVs.
- The max shift of GTVs ranged from 0.06-2.48 mm across all patients.
- The mean shift within the contours was 0.27 mm when averaged across all cases, with the highest mean shift being 0.47 mm.
- **The four GTVs with the greatest maximum shifts were also the four closest to air cavities, as shown in Figure 3.**
- Target volume changes were <5%.

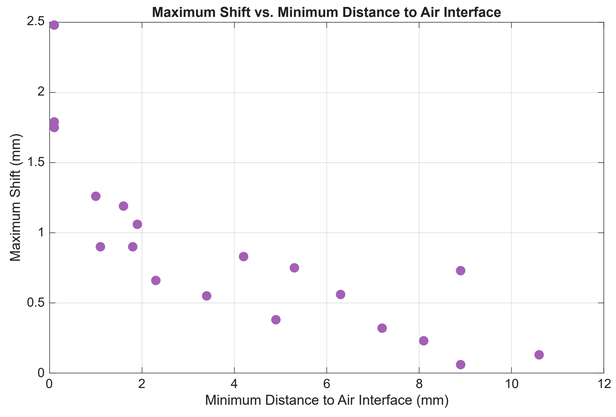

Figure 3: Relationship between maximum geometric shift and minimum tumour distance to an air interface.

Patient	Type	Min (mm)	Mean (mm)	Max (mm)	Range (mm)
1	Met	0.25	0.30	0.38	0.13
2	Met	0.08	0.20	0.55	0.48
3	Met	0.23	0.35	0.56	0.33
4	Met	0.01	0.34	1.19	1.19
5	Met	0.13	0.23	0.32	0.19
6	Met	0.00	0.21	0.66	0.66
7	Met	0.06	0.01	0.13	0.07
8	AN	0.02	0.37	0.90	0.88
9	AN	0.00	0.31	0.75	0.75
10	AN	0.00	0.33	0.90	0.90
11	AN	0.00	0.31	0.73	0.72
12	AN	0.00	0.41	1.26	1.26
13	AN	0.00	0.30	0.83	0.83
14	Pit	0.00	0.32	1.75	1.75
15	Pit	0.00	0.20	1.06	1.06
16	Pit	0.00	0.26	1.79	1.79
17	Pit	0.02	0.47	2.48	2.46
18	Met	0.02	0.03	0.06	0.04
19	Met	0.02	0.11	0.23	0.21

Table 1: Summary statistics of GTV point cloud shifts (mm) for each patient. Highlighted rows are GTVs shown in Fig. 2.

Results: Dosimetric

- Table 2 highlights change in dose and target coverage metrics.
- Across all structures and patients, 84% of all dose-difference values (ΔD_{min}, ΔD_{mean}, ΔD_{med}, ΔD_{max}) were within $\pm 1\%$. The largest change occurred in patient 12's PTV ΔD_{min}.
- Susceptibility-induced distortions generally **reduce target coverage ($V_{95} - V_{100}$) with only minor changes to dose (particularly D_{min})** and minimal impact on normal tissue dose.

Pt	Type	ΔD_{min}	ΔD_{mean}	ΔD_{max}	ΔV_{90}	ΔV_{100}	ΔD_{max} normal tissue
1	Met	0.46	0.57	-0.01	**0.00**	**0.00**	-0.57
2	Met	-1.68	0.62	-0.01	**0.00**	**1.03**	1.87
3	Met	-6.93	-1.89	-0.17	**-7.31**	**-10.10**	0.55
4	Met	2.36	0.72	-0.13	**0.59**	**2.03**	2.11
5	Met	-1.92	-0.35	-0.15	**-0.07**	**-1.82**	0.41
6	Met	0.13	0.48	0.01	**2.05**	**-1.77**	-0.91
7	Met	2.95	-0.07	-0.01	**0.00**	**0.00**	0.28
8	AN	-0.09	-0.08	-0.18	**0.42**	-0.70	-0.16
9	AN	-5.12	-0.41	0.02	**-4.58**	0.21	0.28
10	AN	1.01	0.01	0.02	**-0.69**	-0.61	0.34
11	AN	-0.14	0.45	-0.01	**1.69**	2.50	0.57
12	AN	-9.23	-0.33	-0.01	**-1.87**	0.02	1.81
13	AN	0.53	-0.01	-0.01	**0.12**	-0.68	0.36
14	Pit	-0.94	-0.45	0.00	**-1.66**	-0.53	0.13
15	Pit	-0.03	-0.21	0.00	**-1.45**	-0.44	-0.05
16	Pit	-0.06	0.10	0.00	**-1.90**	-0.95	0.00
17	Pit	0.28	-0.12	0.00	**-0.49**	-1.38	-0.01
18	Met	0.12	0.07	0.01	**0.00**	**0.00**	-0.03
19	Met	-2.56	-0.20	-0.07	**0.00**	**-0.38**	0.37

Table 2: Summary of tumour PTV metrics for all patients (Met = Brain Metastasis, AN = Acoustic Neuroma, Pit = Pituitary Tumour). The PTV metrics are reported in %. Highlighted rows are PTVs corresponding to those shown in Fig. 2.

Conclusion

- Small cranial structures near tissue-air interfaces may have magnetic susceptibility distortions that shift structures by a median value of **0.3 mm with an MRI field strength of 1.5 T and read gradient strength of 4 mT/m.**
  - These distortions result in **minimal dosimetric impact** to stereotactic radiotherapy plans.

References

1. Adjeiwaah M, Bylund M, Lundman JA, et al. Dosimetric Impact of MRI Distortions: A Study on Head and Neck Cancers. Int J Radiat Oncol Biol Phys. 2019;103(4):994-1003. **2.** Stanescu T, Wachowicz K, Jaffray DA. Characterization of tissue magnetic susceptibility-induced distortions for MRIgRT. *Med Phys*. 2012;39(12):7185-7193. **3.** Wachowicz K, Stanescu T, Thomas SD, Fallone BG. Implications of tissue magnetic susceptibility-related distortion on the rotating magnet in an MR-linac design. *Med Phys*. 2010;37(4):1714-1721. **4.** Wang H, Balter J, Cao Y. Patient-induced susceptibility effect on geometric distortion of clinical brain MRI for radiation treatment planning on a 3T scanner. *Phys Med Biol*. 2013;58(3):465-477.