Impact of Six Degrees of Freedom Intrafraction Motion on Target Coverage in Single-Isocenter Multi-Target Stereotactic Radiosurgery

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Iris Rusu MS[1], Hyejoo Kang Ph.D[2], Anupama Chundury MD[2], and John C. Roeske, PhD[2]

(1) Loyola University Medical Center, Maywood, IL, (2) Stritch School of Medicine Loyola University Chicago, Cardinal Bernardin Cancer Center, Loyola University Chicago, Maywood, IL

ABSTRACT

Purpose

To quantify the dosimetric impact of 6DoF intrafractional errors on gross tumor volume (GTV) and planning target volumes (PTV) for single-isocenter multi-target stereotactic radiosurgery (SIMT-SRS) as a function of minimum GTV dose ($Dmin_{GTV}$), volume of target and distance to isocenter.

Methods

Seven spherical GTVs (0.1cc-3.0cc) and the 1mm-margin PTVs were used to generate three SIMT-SRS plans, delivering 20Gy to each PTV, with a $Dmin_{GTV}$ of 22Gy in one plan, 23Gy and 24Gy in the second and third plans. A random number generator simulated 100 translations-rotations within the 1mm/1^0 intrafraction tolerance. Using an open-source Python package, all GTVs/PTVs were translated-rotated around the isocenter according to the generated 6DOF errors. The same translations-rotations were performed around different points in space to mimic target-to-isocenter distances from 0cm to 10cm. For each plan, the dose received by 99% of the displaced target volumes ($D99^{22Gy}_{GTV/PTV}$, $D99^{23Gy}_{GTV/PTV}$ $D99^{24G}_{GTV/PTV}$) were extracted and normalized to the undisplaced value. The average over 100 displacements of the above parameters ($AvgD99^{22Gy}_{GTV/PTV}(\%)$ ($AvgD99^{23Gy}_{GTV/PTV}(\%)$, $AvgD99^{24Gy}_{GTV/PTV}(\%)$), was computed and the 95% confidence interval (CI) was calculated for each distance from isocenter.

Results

The $AvgD99_{GTV}$ (%) and $AvgD99_{PTV}$ (%) decreases with increasing distance from isocenter and decreasing target size, regardless of $Dmin_{GTV}$. Plans with higher $Dmin_{GTV}$ experience larger relative dose coverage loss of GTVs/PTVs compared to plans with lower $Dmin_{GTV}$ for all target sizes and distances from isocenter. Nevertheless, the loss of absolute dose coverage of GTVs and PTVs was reduced for the plans with higher $Dmin_{GTV}$.

Conclusions

In SIMT-SRS, the loss in GTV and PTV dose coverage due to 6DoF intrafraction motion is subject to the interplay effect between $Dmin_{GTV}$, target volume and distance from isocenter. For the same PTV dose, plans delivering higher $Dmin_{GTV}$ are more robust to uncorrected 6DoF intrafraction errors .

AIM

- To provide a robust analysis of the effect of 6DOF intrafraction motion on target dose coverage for SIMT-SRS.
- To quantify the loss in dosimetric coverage by analyzing the interplay effect of dose gradient within the PTV-GTV margin, target volume, distance to isocenter.
- To report statistically significant average of reduction in target dose coverage along with 95% CI as a function of dose gradient within the PTV-GTV margin, target size and distance to isocenter.

METHODS AND MATERIALS

- Seven spherical GTVs (0.1cc-3.0cc) and the corresponding 1mm-margin PTV were simulated and randomly distributed throughout the brain (Figure 1).

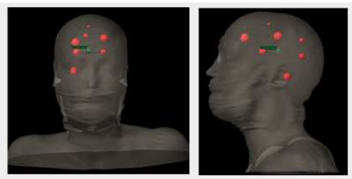

Figure 1. Frontal and lateral view showing the spatial distribution of the GTVs with respect to the isocenter position.

- Three SIMT-SRS plans were created in Eclipse (Varian Medical Systems, Palo Alto, CA) to deliver 20Gy in one fraction to each PTV with a $Dmin_{GTV}$ of 22Gy (Plan1), 23Gy (Plan2) and 24Gy (Plan3).
- Paddick Gradient Index ($GI_{Paddick}$), the Dose Gradient Index (DGI) and normal brain V12 volume were reported for all plans.
- Dose gradient inside the 1mm PTV to GTV margin was quantified by computing $Dmin_{GTV}/Dmin_{PTV}$ ratio for each target in all 3 plans.
- A random number generator simulated 100 potential combinations of 6DoF within intrafraction motion tolerance of 1mm and 1^0 (Figure2).

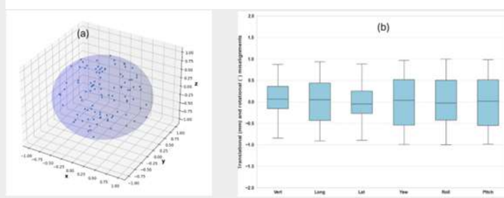

Figure 2. Simulated intrafraction misalignments. (a) Spatial distribution of the 3D translations within a sphere of 1mm radius. (b) Box plot of translational (mm) and rotational (^{0}) errors, displaying median, top and bottom of the lower and upper quartiles.

- All GTVs/PTVs were translated-rotated around the isocenter according to the generated 6DOF.
- The dose received by 99% of each displaced volume ($D99\%_{GTV}$, $D99\%_{PTV}$) was extracted from the dose file and normalized to the undisplaced value.
- $D99\%_{GTV}$ was averaged over 100 displacements ($AverageD99\%_{GTV}$ $AverageD99\%_{PTV}$) and 95% CI was calculated.
- The same translations-rotations were performed around different points in space to mimic different target-to-isocenter distances.
- $AverageD99\%_{GTV}$ $AverageD99\%_{PTV}$ were reported for each GTV and PTV volume for target-to-isocenter distances from 0cm to 10cm.

RESULTS

- Table 1 shows that Plan 3($Dmin_{GTV}$=24Gy) achieved the stepper dose fall off outside all targets, superior DGI and reduced V12Gy when when compared to Plan 1 ($Dmin_{GTV}$=22Gy) and Plan2 ($Dmin_{GTV}$=23Gy).

Target Volume (cc)		Dmax (Gy)			GI Paddick			DGI (ideal, minimum value)			V12Gy (<10cc tolerance)		
		Plan1 $Dmin_{GTV}$=22Gy	Plan2 $Dmin_{GTV}$=23Gy	Plan 3 $Dmin_{GTV}$=24Gy	Plan1 $Dmin_{GTV}$=22Gy	Plan2 $Dmin_{GTV}$=23Gy	Plan 3 $Dmin_{GTV}$=24Gy	Plan1 $Dmin_{GTV}$=22Gy	Plan2 $Dmin_{GTV}$=23Gy	Plan 3 $Dmin_{GTV}$=24Gy	Plan1 $Dmin_{GTV}$=22Gy	Plan2 $Dmin_{GTV}$=23Gy	Plan 3 $Dmin_{GTV}$=24Gy
GTV1/PTV1	0.1/0.2	27.2	27.3	27.5	6.3	6.2	6.0	91.4 (91, 83)	92.2 (91, 83)	93.0 (91, 83)	1.5	1.4	1.4
GTV2/PTV2	0.5/0.9	27.6	27.6	28.3	3.8	4.1	3.5	93.6 (91, 83)	95.1 (91, 83)	96.1 (91, 83)	2.8	2.8	2.6
GTV3/PTV3	1.0/1.7	27.7	27.4	28.0	3.3	3.2	3.1	92.6 (81, 72)	94.0 (81, 72)	94.3 (81, 72)	3.8	3.9	3.7
GTV4/PTV4	1.5/2.4	27.9	28.2	27.8	3.2	3.1	3.0	89.7 (81, 72)	92.6 (81, 72)	92.0 (81, 72)	5.1	5.1	4.3
GTV5/PTV5	2.0/3.1	28.4	27.4	28.9	3.1	2.9	2.9	87.9 (74, 65)	90.8 (74, 65)	90.5 (74, 65)	6.2	6.0	5.6
GTV6/PTV6	2.5/3.8	27.5	27.8	28.3	3.2	3.0	2.9	87.6 (74, 65)	87.5 (74, 65)	89.8 (74, 65)	7.3	7.2	6.3
GTV7/PTV7	3.0/4.3	28.3	28.0	28.9	2.8	2.8	2.7	88.0 (74, 65)	89.6 (74, 65)	88.8 (74, 65)	7.6	8.0	7.0

Table 1. Comparison of D_{max}(Gy), $GI_{Paddick}$, DGI and V12Gy of the three SIMT-SRS plans

Figure 3a and 3b show:

- Relative loss in $AvgD99_{GTV}$(%) for different dose gradient plans within the 1mm margin as a function of distance to isocenter for the smallest (GTV1 = 0.1cc) and largest (GTV7 = 3.0cc) volume.
- Increasing loss in relative target dose with increasing distance to isocenter and decreasing target size.
- The relative loss in $AvgD99_{GTV}$(%) is reduced for shallower dose gradient plans inside the 1mm PTV to GTV margin when compared to plans with steeper gradient.

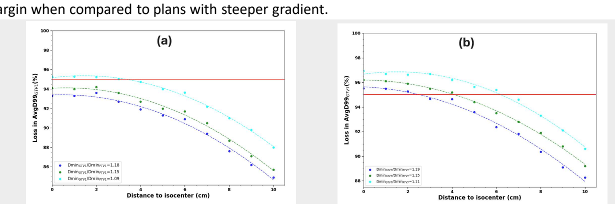

Figure 3. Loss in relative AvgD99(%) of GTV1 (3a) and GTV7 (3b) as a function of distance from isocenter, for different dose gradients inside the target volume ($Dmin_{GTV}/Dmin_{PTV}$), with reference to 5% tolerance value.

Figure 4a and 4b show:

- Absolute loss in $AverageD99\%_{GTV}$ (Gy) for the 3 dose gradient plans as a function of distance to isocenter for the smallest (GTV1 = 0.1cc) and largest (GTV7 = 3.0cc) volume.
- The absolute loss in $AvgD99_{GTV}$(Gy) is reduced for plans achieving stepper dose gradient within the 1mm PTV to GTV margin for all target sized and distance to isocenter.

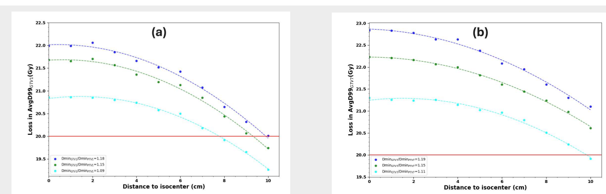

Figure 4. Loss in absolute AvgD99(Gy) of GTV1 (4a) and GTV7 (4b) as a function of distance from isocenter, for different dose gradients inside the target volume ($Dmin_{GTV}/Dmin_{PTV}$), with reference to 20Gy prescription dose.

CONCLUSIONS

- The loss in target dose coverage due to 6DoF intrafraction motion is subject to the interplay effect between dose gradient within the target, target volume and distance from isocenter.
- Treatment plans generated with a stepper dose gradient within the PTV to GTV margin:
  - are more robust to uncorrected 6DoF intrafraction errors.
  - outperform the shallow dose gradient plans by providing better local control with higher target dose, superior dose falloff outside the target and reduced risk of radiation necrosis within the normal brain.

REFERENCES

1. Nakano H. et al. DOI: https://doi.org/10.1002/acm2.13081
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CONTACT INFORMATION

Iris Rusu irusu@lumc.edu