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The Dancing Cord: Inherent Spinal Cord Motion and Its Effect on Cord Dose in Spine SBRT

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UWMC is located on Portage Bay, Seattle WA



Regional Campuses



Disclosures-None



Learner Outcomes

1. Explain the dose limitations to the spinal cord for spinal stereotactic body radiation therapy
2. Discuss and assess motion of the spinal cord
3. Explain the recommended planning organ at risk margin



Spine Metastases

- Common complication of cancer
- 40% of cancer patients
- Major functional morbidity
- Pain
- Vertebral fractures
- Myelopathy from compression



Spine SBRT

- Paradigm shift
- High doses
- Highly conformal radiotherapy
- Steep dose gradient



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Spine SBRT Indications

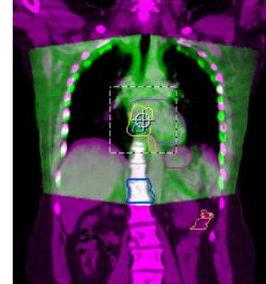
- Palliative symptom relief
- Durable local control
- Oligoprogression
- Potential augmentation of the immune response



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Spinal SBRT

- Rapid advancement in precise on board imaging
- Spinal SBRT effective and non-invasive treatment option



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Limiting Factor

- Tolerance to spinal cord
- Risk of complications due to myelopathy
- Biggest concern



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Established dose constraints for safe practices

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HyTEC Organ-Specific Paper

Spinal Cord Dose Tolerance to Stereotactic Body Radiation Therapy

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De novo cases

8 Sahgal et al.

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Table 3 Spinal cord and thecal sac D_{max} values recommended in previous publications compared with model-derived limits

| No. fractions | Existing expert-based recommendations for D_{max} | | Model-based limits for D_{max} , derived from clinical data | | Approximate Risk of RM, % |
|---------------|---|------------------------------|---|--------------------------------------|---------------------------|
| | AAPM TG101 ⁵ | Kim et al 2017 ⁵⁶ | Sahgal 2013 ⁵ | Katsoulakis–Gibbs model ⁶ | |
| | Gy | Gy | LQ, $\alpha/\beta = 2$ Gy | LQ, $\alpha/\beta = 2$ Gy | |
| 1 | 14 | 14 | 12.4 | 14 | 1-5 |
| 2 | | 18.3 | 17 | 19.3 | 1-5 |
| 3 | 21.9 | 22.5 | 20.3 | 23.1 | 1-5 |
| 4 | | 25.6 | 23 | 26.2 | 1-5 |
| 5 | 30 | 28 | 25.3 | 28.8 | 1-5 |

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Re-irradiation cases

Table 3 Spinal cord and thecal sac D_{max} values recommended in previous publications compared with model-derived limits

| No. fractions | Existing expert-based recommendations for D_{max} | | Model-based limits for D_{max} derived from clinical data | | |
|---------------|---|------------------------------|---|--------------------------------------|------------------|
| | AAPM TG101 ⁵ | Kim et al 2017 ⁵⁶ | Sahgal 2013 [*] | Katsoulakis–Gibbs model [*] | Approximate Risk |
| | Gy | Gy | LQ, $\alpha/\beta = 2$ Gy | LQ, $\alpha/\beta = 2$ Gy | of RM, % |
| 1 | 14 | 14 | 12.4 | 14 | 1-5 |
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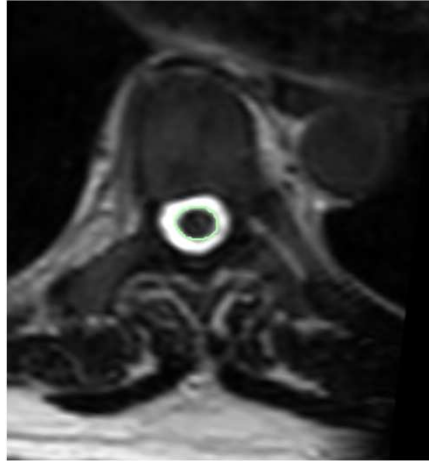
Spinal Cord contour

- Correct and high-precision delineation
- Spatial relationship to planning volume
- Critical to the spinal cord dose limit



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MRI T2 weighted images



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CT myelogram if patient has hardware

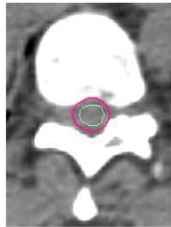


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Safety Margin for Spinal Cord

Planning organ at risk volume (PRV)

- No standardization
- Recommendations are variable
- Practice patterns 0 to 2 mm expansions

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Most Focus

SBRT Spine

- Set up uncertainties
- Spinal cord delineation
- Not much attention to organ motion

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Spinal Cord Location

SBRT Spine

- Within mm from PTV
- Steep dose gradient region
- Organ motion may exert effect on dose
- Physiological motion spinal cord
- What dose effect does motion have?
- Compared to T2-weighted MRI

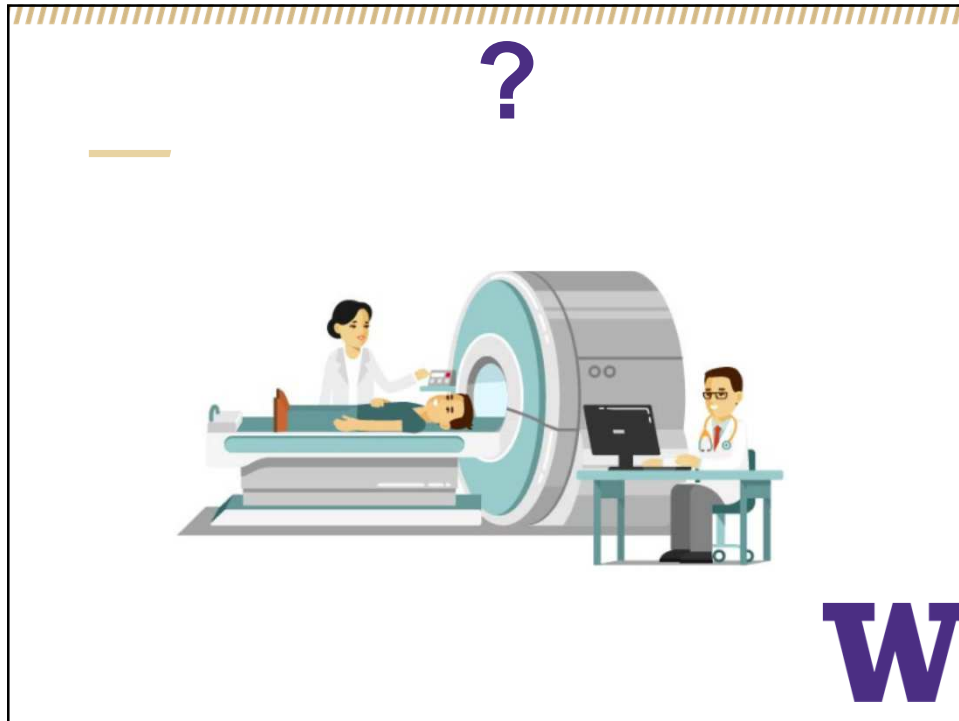


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Evaluate pattern Spinal Cord Motion and dose effects in SBRT patients

- Dynamic MRI
- Compared dosimetric parameters for moving and static spinal cord
- T2-weighted MRI
- Derive recommendations for PRV margins
- Taking into account motion

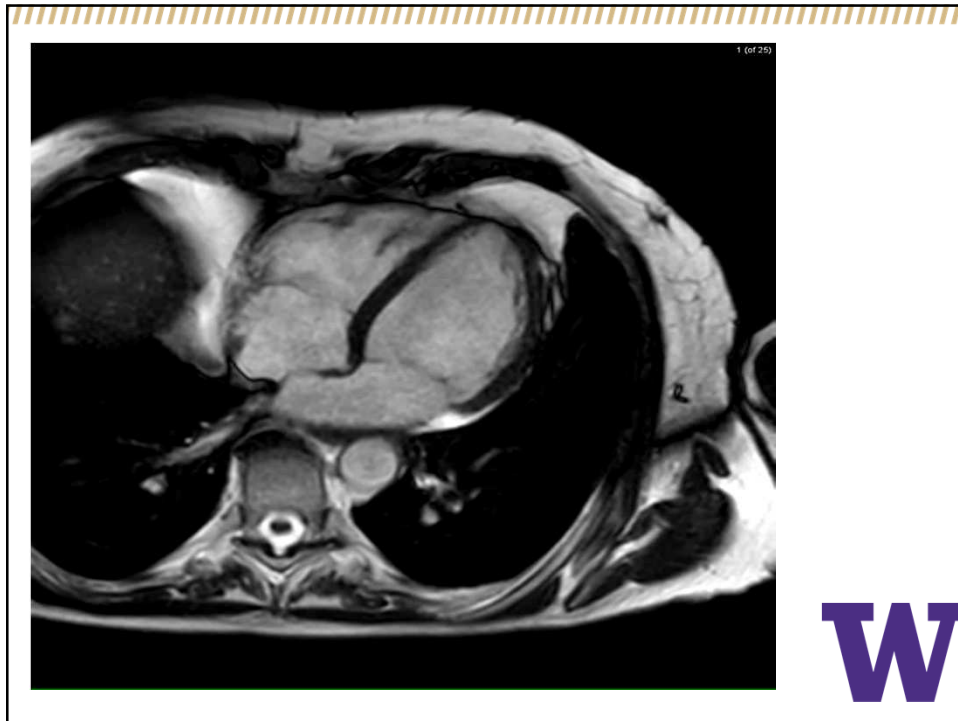
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MRI Cardiac Gating

- Cine images show motion throughout cardiac cycle
- Cardiac cycle captured in multiple segments
- ECG leads on patient
- MRI set to acquire images from ECG trigger
- Balanced Fast Field Echo (BFFE) advanced MRI sequence
- BFFE cardiac gating, exquisite spatial resolution and tissue contrast
- Cine gathered over several heart beats, 10-20 seconds
- Final movie sequence of captured images

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MRI Spinal Cord gating

- Spinal cord moves during cardiac cycle
- Captured images continuously
- Peripheral monitor (Pulse Oximeter)
- MRI set to acquire images from second heart beat (diastole)
- Balanced Fast Field Echo (BFFE) used
- Cine gathered over several times during cardiac cycle
- Final movie sequence of captured images



Spinal cord motion

- Motion multifactorial
- CSF pulsation
- Respiration
- Arterial pulsation
- Biomechanical effects-compliance of CNS
- Existing literature reports motion < 1mm
- MRI and myelogram allow spinal cord delineation from CSF
- Cord motion limited by temporal resolution



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Preliminary results of this study were presented at the Radiological Society of North America (RSNA) 104th Scientific Assembly and Annual Meeting, November 25-30, 2019 in Chicago, Illinois, and at the 2019 Radiosurgery Society Annual Scientific Meeting, March 27-28, 2019, in San Diego, California.

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The Dancing Cord: Inherent Spinal Cord Motion and Its Effect on Cord Dose in Spine Stereotactic Body Radiation Therapy

BACKGROUND: Spinal cord dose limits are critically important for the safe practice of spine stereotactic body radiotherapy (SBRT). However, the effect of inherent spinal cord motion on cord dose in SBRT is unknown.

OBJECTIVE: To assess the effects of cord motion on spinal cord dose in SBRT.

METHODS: Dynamic balanced fast field echo (BFFE) magnetic resonance imaging (MRI) was obtained in 21 spine metastasis patients treated with SBRT. Planning computed tomography (CT), conventional static T2-weighted MRI, BFFE MRI, and dose planning data were coregistered. Spinal cord from the dynamic BFFE images ($cord_{dyn}$) was compared with the T2-weighted MRI ($cord_{stat}$) to analyze motion of $cord_{dyn}$ beyond the $cord_{stat}$ (Dice coefficient, Jaccard index), and beyond $cord_{stat}$ with added planning organ at risk volume (PRV) margins. Cord dose was compared between $cord_{stat}$ and $cord_{dyn}$ (Wilcoxon signed-rank test).

RESULTS: Dice coefficient (0.70-0.95, median 0.87) and Jaccard index (0.54-0.90, median 0.77) demonstrated motion of $cord_{dyn}$ beyond $cord_{stat}$. In 62% of the patients (13/21), the dose to $cord_{dyn}$ exceeded that of $cord_{stat}$ by 0.6% to 13.8% (median 4.3%). The $cord_{dyn}$ spatially excused outside the 1-mm PRV margin of $cord_{stat}$ in 9 patients (43%); among these dose to $cord_{dyn}$ exceeded dose to $cord_{stat}$ + 1-mm PRV margin in 78% of the patients (7/9). $cord_{dyn}$ did not excuse outside the 1.5-mm or 2-mm PRV $cord_{stat}$ margin.

CONCLUSION: Spinal cord motion may contribute to increases in radiation dose to the cord from SBRT for spine metastasis. A PRV margin of at least 1.5 to 2 mm surrounding the cord should be strongly considered to account for inherent spinal cord motion.

KEY WORDS: Ablative radiotherapy, Motion, MR imaging, Organ motion, Patient positioning, Secondary spine metastasis, Spinal cord, Spinal cord physiology, Spinal neoplasms, Stereotactic radiation therapy

Neurosurgery 01:1-10, 2020

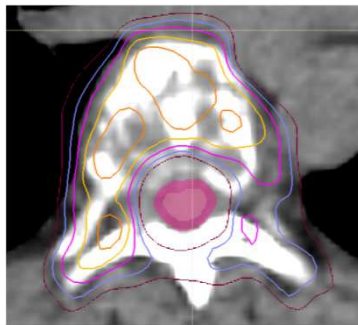
DOI:10.1093/neuros/nyaa010

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Methods

- Retrospective study
- 21 adult patients
- IRB approval including patient consent
- All patients planned SBRT-tailored MRI protocol



Characteristics

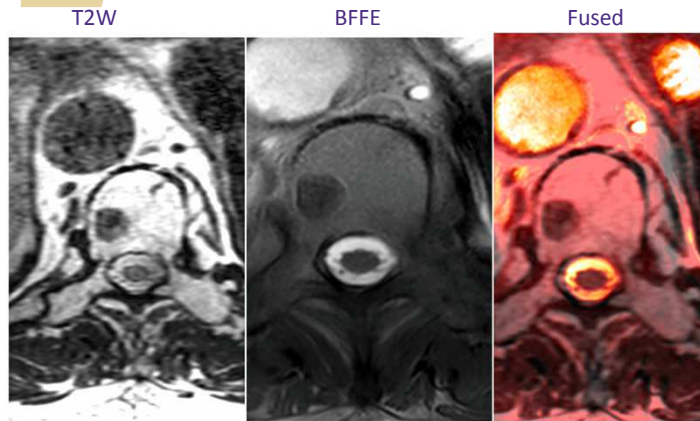
| Characteristic | No. of patients | Percentage |
|-----------------------|-----------------|------------|
| Tumor location | | |
| C-spine | 3 | 14 |
| T-spine | 17 | 81 |
| L-spine ^a | 1 | 5 |

| Primary tumor and histology^b | | |
|--|----|----|
| Breast carcinoma | 4 | 19 |
| Prostate carcinoma | 3 | 14 |
| Thyroid carcinoma | 3 | 14 |
| Gynecologic tumor ^c | 3 | 14 |
| Hepatocellular carcinoma | 2 | 10 |
| Renal cell carcinoma | 2 | 10 |
| Sarcomatous tumor ^d | 2 | 10 |
| Lung carcinoma | 1 | 5 |
| Pheochromocytoma | 1 | 5 |
| Fractionation schedule | | |
| 3-Fraction regimen | 11 | 52 |
| 5-Fraction regimen | 10 | 48 |

- Targets and normal tissue contoured in MIM
- Coregistration of TPCT and T2-weighted MRI in MIM, peer reviewed
- PRV margin 2 mm added to spinal cord
- IMRT/VMAT planning in RayStation
- Dose prescribed per routine SBRT dosing standards
- Maximum pixel dose to spinal cord PRV 20 Gy in 3 fxs, 25 Gy in 5 fxs



Image co-registration – T2W images and (15 image) BFFE were fused together for each patient



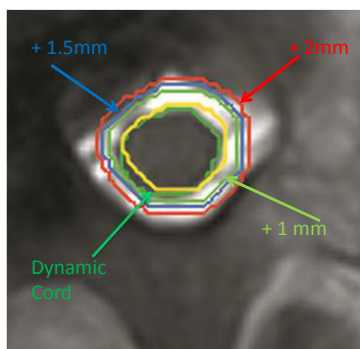
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Image Evaluation and Spinal Cord_{dyn} Contours

- The spinal cord (cord_{dyn}) contoured on (15 images) BFFE and on the static T-2 weighted images (cord_{stat})
- Peer reviewed
- Registered TPCT to transfer contours
- Treatment plans were coregistered to 15 BFFE images
- On the static images, 1, 1.5, and 2 mm expansion on cord_{stat}

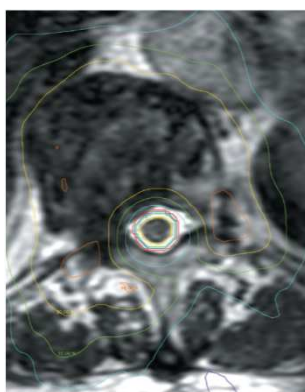
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BFFE image Hypothetical PRV margins added



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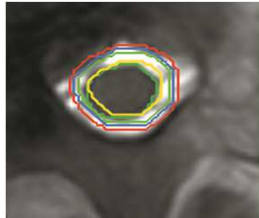
Dose Distribution on BFFE images



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Materials and Method-Calculations (motion)

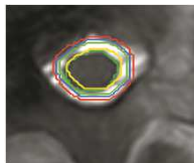
- The motion of the cord was quantified by comparing the coordinates of the centroids of the dynamic cord images
- Average of centroids over 15 frames was considered the “zero point” of dynamic cord motion
- Dice and Jaccard coefficients were calculated between static cord and each frame of dynamic cord

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Materials and Method-Calculations (dose)

Maximum dose received by the cord was calculated for:

- Static cord image and each frame of the dynamic cord images
- 1 mm, 1.5 mm and 2 mm expansions
- EQD2 dose
- Average of 15 frames (average dose)
- Maximum of 15 frames (max dose)

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Results-Dice and Jaccard Coefficients

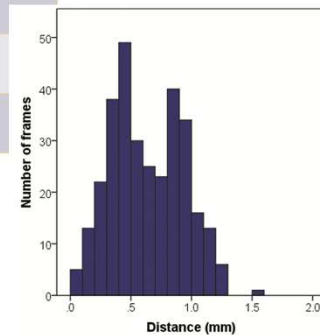
- **Dice**
 - Median: 0.87
 - Range: 0.70-0.95
- **Jaccard**
 - Median: 0.77
 - Range: 0.54-0.90

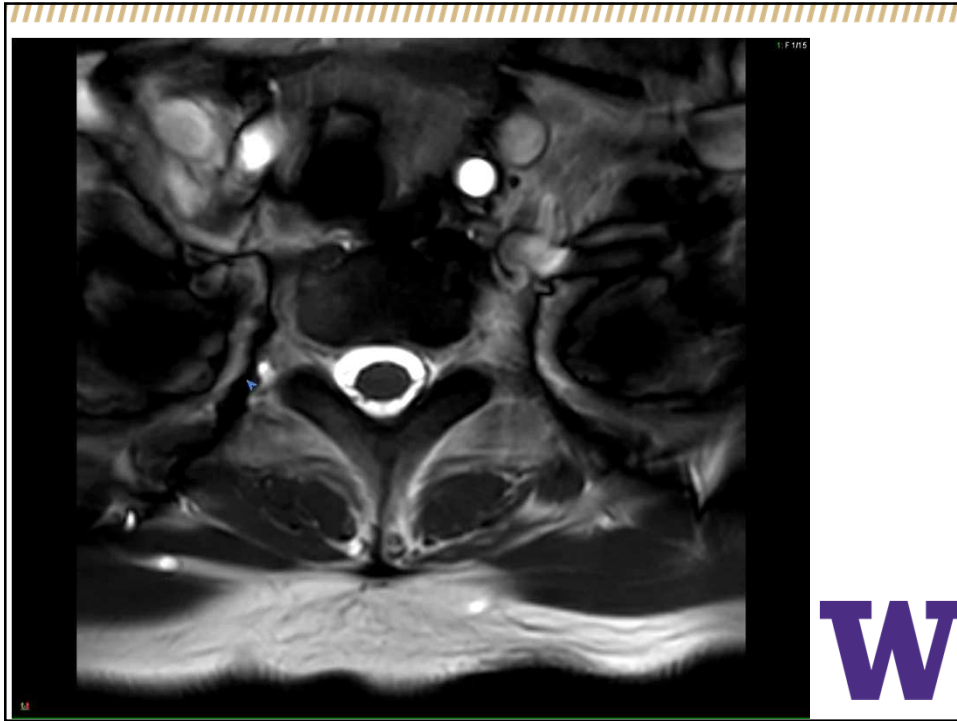


Results-Centroid motion

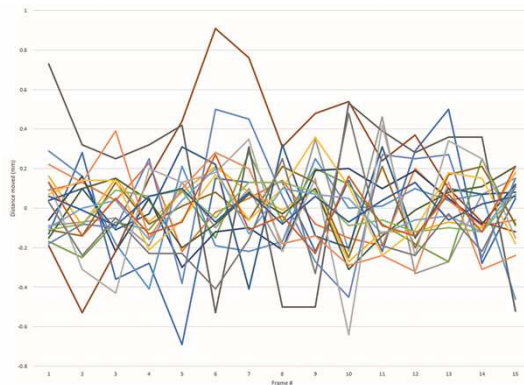
| | Median | Min | Max |
|------------------|--------|-----|-----|
| Left-to-right* | 0.3 | 0 | 1.1 |
| Anteroposterior* | 0.5 | 0.1 | 1.5 |
| Total motion | 0.6 | 0 | 1.5 |

AP motion significantly greater than right to left
 p = .04

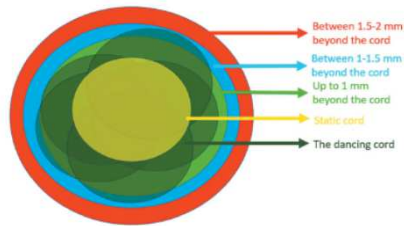




Pattern of Spinal Cord Motion 15 dynamic BFFE images



Schematic “Dancing Cord”



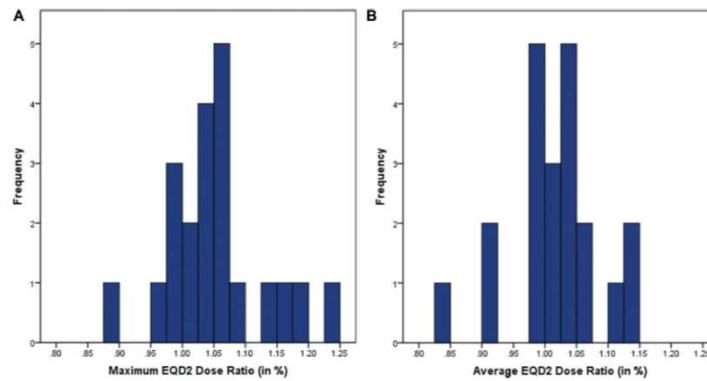
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Results-Dose Excess

- In 13 patients (62%), average EQD2 dose received by the cord exceeded that of the static cord in at least 1 frame.
- Dose exceeded by 4.3% (median) of static cord dose (Max: 13.8%)
- When considering maximum EQD2 dose, this changed to 16 patients (76%) with dose exceeded by 5.7% (median, range 1.4-23.5%)
- In 9 patients (43%), maximum cord dose in dynamic images was greater than the maximum dose in 1 mm PRV.
- No patients had maximum cord dose exceeding that of 1.5 mm margin.

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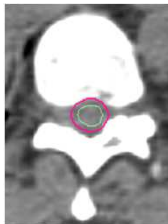
Results: Spinal cord doses



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1st Investigative study on spinal cord motion

- Assessment on dosimetric effects of spinal cord motion
- High-precision MRI-based cord delineation
- Used BFFE
- UWMC observations on cord motion within previous reported values
- Tseng et al reported no movement beyond 1.5 mm



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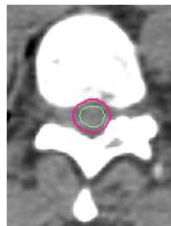
Implications for Practice

- Results are generalized for patients with metastatic spinal lesions in SBRT
- Based on unlikely excursion of spinal canal beyond 1.5 to 2 mm
- Recommend applying a 1.5 to 2 mm margin around spinal cord
- PRV margin

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PRV margin 1mm

- Inadequate margin
- Based on observation that cord moves beyond 1 mm
- 43% of sampled patients cord moves beyond 1mm
- Which would have resulted in 78% excess dose to the spinal cord

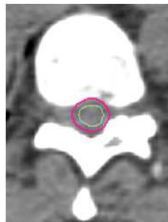
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- Physiological organ motion and dosimetric consequences have gained much attention in radiation oncology community
- Spinal cord motion and impact on cord dose has not much attention
- Cord motion not incorporated into SBRT planning
- BFFE offers exquisite detail to delineate CSF and spinal cord for dynamic imaging

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Conclusion

- UWMC finding show that spinal motion contributed to dose effects to the spinal cord
- Recommend a 1.5 to 2 mm cord PRV margin
- UWMC uses 2 mm for all SBRT spine patients
- If available, short cardiac gated MRI
- Future studies are needed to confirm our results

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Thank you!

- Murat Alp Oztek, MD
- Nina Mayr, MD
- Simon Lo, MD
- William Yuh, MD



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Thank you AAMD members!



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